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M. A. McVeign March 1979

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for

National Aeronautics and Space Administration
Ames Research Center

by

PHILADELPHIA. PENNSYLVANIA



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A-1 A-2 A-3 A-4 A-5 B-1 B-2 B-3											
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ABSTRACT

A mathematical model of a hingeless tilting rotor is presented. The model was obtained by a systematic curve-fit procedure applied to an extensive set of model-scale wind tunnel data. The math model equations were used in a real-time flight simulation model of a hingeless tilt rotor XV-15 to assess changes in flying qualities compared to those obtained using a previous rotor model. Extensive plots of the rotor derivatives are given. Discussions of attempts to apply multivariable linear regression techniques to the data and the use of an analytical rotor representation are included.

FOREWORD

This report was prepared by the Boeing Vertol Company of Philadelphia, Pennsylvania for the National Aeronautics and Space Administration, Ames Research Center under NASA Contract NAS2-9015.

Mr. T. Galloway of Ames Research Center was technical monitor for this work. Mr. M. A. McVeigh was the project engineer and the Boeing program manager was Mr. H. R. Alexander.

TABLE OF CONTENTS

	Page
Abstract	VIII
Foreword	IX
List of Figures	XI
List of Tables	XIX
List of Symbols	xx
Summary	1
1.0 Introduction	2
2.0 Data Base	4
3.0 Reduction Method and Comparison with Test	Data 5
3.1 Determination of the Values of the Coefficients, C_{FR}	6
3.2 Math Model Equations	7
. 3.3 Comparison with the Test Data	9
4.0 Effect on Aircraft Trim and Stability	12
5.0 Conclusions and Recommendations	14
6.0 References	16
Appendix A. Application of Linear Regression Techniques	A-1
Appendix B. Simplified Rotor Analysis	B-1
Appendix C. Listing of the Rotor Math Model	C-1

LIST OF FIGURES

Figure Number	Title	Page
2.1	1/4.622 Scale Model Ir talled in the Wind Tunnel	35
2.2	Scope of Test of Reference 3 .	36
3.1	Variation of Reference Angle of Attack with $\mu\cos\alpha$	•
3.2	Definition of Reference Values of Cyclic and RPM	30
3.3	Variation of $\partial C_m/\partial A_1$, with $\mu \cos \alpha$	39
3.4	Variation of $3C_{\pi}/3B_{1}$, with $\mu\cos\alpha$	40
3.5	Variation of aC_m/aa with ucosa	41
3.6	Variation of aC_m/aRPM with µcosa	42
3.7	Variation of $\partial C_p/\partial A_1$ with $\mu\cos\alpha$	43
3.8	Variation of $3C_p/3B_1$ with $\mu\cos\alpha$	44
3.9	Variation of aCp/aα with μcosα	45
3.10	Variation of 3Cp/3RPM with ucosa	46
3.11	Variation of $\partial C_{NF}/\partial A_{\gamma}$ with $u\cos\alpha$	47
3.12	Variation of $3C_{NF}^{NF}/3B_{1}^{2}$ with $\mu\cos\alpha$	48
3.13	Variation of 3C _{NF} /3a with µcosa	49
3.14	Variation of ${}_{3}C_{NF}^{-/3}\psi$ with ${}_{4}cos\alpha$	50
3.15	Variation of 3C _{NF} /3RPM with ucosa	51
3.16	Variation of $\partial C_{SF}/\partial A_1$ with $u\cos\alpha$	52
3.17	Variation of aC _{SF} /3B ₁ with μcosα	53
	Variation of $\partial C_{SF}/\partial \alpha$ with $\mu\cos\alpha$	54
3.19		55
3.20	Variation of aC _{SF} /aRPM with μcosα	56
3.21	Variation of aC _{pM} /aA ₁ with μcosα	57
	Variation of $3C_{pM}/3B_1$ with $u\cos\alpha$	58
3.23		59
	Variation of 3C _{pm} /3ψ with ucosα	60
	Variation of 3Cpm/3RPM with ucosa	61
	Variation of $3C_{YM}/3A_1$ with ucosa	62
	Variation of 3C _{VM} /3B ₁ with ucosa	63
	7 M I	

Figure Number	<u>Title</u>	Page
3.28	Variation of aC _{YM} /aα with μcosα	64
3.29	Variation of $\partial C_{VM}^{IM}/\partial \psi$ with $\mu \cos \alpha$	65
3.30	Variation of $\partial C_{VM}^{IM}/\partial RPM$ with $\mu \cos \alpha$	66
3.31	Variation of $\partial F_{RM}/\partial A_1$ with $\mu\cos\alpha$	67
3.32	Variation of aF _{BM} /aB ₁ with μcosα	68
3.33	Variation of ∂F _{BM} /∂α with μcosα	69
3.34	Variation of $\partial F_{\rm BM}/\partial \psi$ with μcosα	70
3.35	Variation of $\frac{BM}{BM}/2A_1$ with $\mu\cos\alpha$	71
3.36	Variation of aC _{BM} /aB ₁ with μcosα	72
3.37	Variation of 3C BM/3 with µcos a	73
3.38	Variation of 3C _{BM} /3ψ with μcosα	74
3.39	Variation of Corrected Thrust Coefficient with Collective Pitch	75
3.40	Corrected Power Coefficient versus Corrected Thrust Coefficient	76
3.41	Corrected Normal Force Coefficient versus Corrected Thrust Coefficient	77
3.42	Corrected Sideforce Coefficient versus Corrected Thrust Coefficient	78
3.43	Corrected Pitching Moment Coefficient versus Corrected Thrust Coefficient	79
3.44	Corrected Yawing Moment Coefficient versus Corrected Thrust Coefficient	80
3.45	Variation of the Reduced Pitching Moment Coefficient at Zero Thrust with using	81
3.46	Illustration of Method of Fitting the Reduced Data	82
3.47	Thrust Coefficient Correlation - Collective Sweeps	83
3.48	Variation of Estimated and Test Values of Power Coefficient with Thrust Coefficient	84
3.49	Variation of Estimated and Test Values of Normal Force Coefficient with Thrust Coefficient	85
3.50	Variation of Estimated and Test Values of	86

Figure Number	Title	Page
3.51	Variation of Estimated and Test Values of Pitching Moment Coefficient with Thrust Coefficient	87
3.52	Variation of Estimated and Test Values of Yawing Moment Coefficient with Thrust Coefficient	88
3.53	Left Rotor Thrust Coefficient Versus Lateral Cyclic Pitch. I _N = 90° Hover.	89
3.54	Left Rotor Power Coefficient Versus Lateral Cyclic Pitch. I _N = 90° Hover.	90
3.55	Left Rotor Normal Porce Coefficient Versus Lateral Cyclic Pitch. I _N = 90° Hover.	91
3.56	Left Rotor Side Force Coefficient Versus Lateral Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	92
3.57	Left Rotor Pitch Moment Coefficient Versus Lateral Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	93
3.58	Left Rotor Yaw Moment Coefficient Versus Lateral Cyclic Pitch: $I_N = 90^{\circ}$ Hover.	94
3.59	Left Rotor Thrust Coefficient Versus Longitudinal Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	3 5'
3.60	Left Rotor Power Coefficient Versus Longitudinal Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	96
3.61	Left Rotor Normal Force Coefficient Versus Longitudinal Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	97
3.62	Left Rotor Side Force Coefficient Versus Longitudinal Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	98
3.63	Left Rotor Pitch Moment Coefficient Versus Longitudinal Cyclic Pitch. $I_N = 90^{\circ}$ Hover.	99
3.64	Left Rotor Yaw Moment Coefficient Versus Longitudinal Cyclic Pitch. $I_{M} = 90^{\circ}$ Hover.	100
3.65	Left Rotor Thrust Coefficient Versus Collective Pitch. $I_N = 90^{\circ}$ Hover.	101
3.66	Left Rotor Power Coefficient Versus Collective Pitch. $I_N = 90^{\circ}$ Hover.	102
3.67	•	103
3.68	••	104

Figure Number	Tille	Page
3.69	Left Rotor Pitching Moment Coefficient Versus Collective Fitch. $I_N = 90^{\circ}$ Hover.	105
3.70	Left Rotor Yaw Moment Coefficient Versus Collective Pitch. $I_N = 90^{\circ}$ Hover.	106
3.71	Left Rotor Thrust Coefficient Vs. Left Rotor Lat. Cyclic ~ Degrees	107
3.72	Left Rotor Power Coefficient Vs. Left Rotor Lat. Cyclic ∿ Degrees	108
3.73	Left Rotor Normal Force Coefficient Vs. Left Rotor Lat. Cyclic ~ Degrees	109
3.74	Left Rotor Side Force Coefficient Vs. Left Rotor Lat. Cyclic ∿ Degrees	110
3.75	Left Rotor Pitching Moment Coefficient Vs. Left Roto Lat. Cyclic ∿ Degrees	111
3.76	Left Rotor Yawing Moment Coefficient Vs. Left Rotor Lat. Cyclic ∿ Degrees	112
3.77	Left Rotor Thrust Coefficient Vs. Left Rotor Long. Cyclic ${\scriptstyle \sim}$ Degrees	113
3.78	Left Rotor Power Coefficient Vs. Left Rotor Long. Cyclic ∿ Degrees	114
3.79	Left Rotor Normal Force Coefficient Vs. Left Rotor Long. Cyclic ~ Degrees	115
3.80	Left Rotor Side Force Coefficient Vs. Left Rotor Long. Cyclic ~ Degrees	116
3.81	Left Rotor Pitching Moment Vs. Left Rotor Long. Cyclic \sim Degrees	117
3.82	Left Rotor Yawing Moment Vs. Left Rotor Long. Cyclic $ ^{\wedge}$ Degrees	118
3.83	Left Rotor Thrust Coefficient Vs. Left Rotor Collective ~ Degrees	119
3.84	Left Rotor Power Coefficient Vs. Left Rotor Collective ∿ Degrees	120
3.85	Left Rotor Normal Force Coefficient Vs. Left Rotor Collective \sim Degrees	121
3.86	Left Rotor Side Force Coefficient Vs. Left Rotor Collective \sim Degrees	122
3.87	Left Rotor Pitching Moment Coefficient Vs. Left Rotor Collective & Degrees	123

Figure Number	Title	Page
3.88	Left Rotor Yawing Moment Coefficient Vs. Left Rotor Collective \sim Degrees	124
3.89	Left Rotor Thrust Coefficient Vs. Angle of Attack	125
3.90	Left Rotor Power Coefficient Vs. Angle of Attack	126
3.91	Left Rotor Normal Force Coefficient Vs. Angle of Attack	127
3.92	Left Rotor Side Force Coefficient Vs. Angle of Attack	128
3.93	Left Rotor Pitching Moment Vs. Angle of Attack	129
3.94	Left Rotor Yawing Moment Vs. Angle of Attack	130
3.95	Left Rotor Thrust Coefficient Vs. Yaw Angle ^`Degrees	131
3.96	Left Rotor Power Coefficient Vs. Yaw Angle ~ Degrees	132
3.97	Left Rotor Normal Force Coefficient Vs. Yaw Angle ~ Degrees	133
3.98	Left Rotor Side Force Coefficient Vs. Yaw Angle ~ Degrees	134
3.99	Left Rotor Pitching Moment Vs. Yaw Angle ∿ Degrees	135
3.100	Left Rotor Yawing Moment Vs. Yaw Angle ∿ Degrees	136
3.101	Left Rotor Thrust Coefficient Vs. Rotor RPM	137
3.102	Left Rotor Power Coefficient Vs. Rotor RPM	138
3.103	Left Rotor Normal Force Coefficient Vs. Rotor RPM	139
3.104	Left Rotor Side Force Coefficient Vs. Rotor RPM	140
3.105	Left Rotor Pitching Moment Coefficient Vs. Rotor RPM	141
3.106	Left Rotor Yawing Moment Coefficient Vs. Rotor RPM	142

Figure Number	Title	Page
3.107	Left Rotor Thrust Coefficient Versus Left Rotor Long. Cyclic \sim Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	143
3.108	Left Rotor Power Coefficient Versus Left Rotor Long. Cyclic ∿ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	144
3.109	Left Rotor Normal Force Coefficient Versus Left Rotor Long. Cyclic ~ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	145
3.110	Left Rotor Side Force Coefficient Versus Left Rotor Long. Cyclic ∿ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	146
3.111	Left Rotor Pitching Moment Versus Left Rotor Long. Cyclic ∿ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	147
3.112	Left Rotor Yawing Moment Versus Left Rotor Long. Cyclic ∿ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	148
3.113	Left Rotor Thrust Coefficient Versus Left Rotor Collective \sim Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	149
3.114	Left Rotor Power Coefficient Versus Left Rotor Collective ∿ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	150
3.115	Left Rotor Normal Force Coefficient Versus Left Rotor Collective \sim Degrees. I = 15°. Full Scale Airspeed 180 Knots.	151
3.116	Left Rotor Side Force Coefficient Versus Left Rotor Collective \sim Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	152
3.117	Left Rotor Pitching Moment Coefficient Versus Left Rotor Collective γ Degrees. I $_{ m N}$ = 15°. Full Scale Airspeed 180 Knots.	153
3.118	Left Rotor Yawing Moment Coefficient Versus Left Rotor Collective ~ Degrees. I _N = 15°. Full Scale Airspeed 180 Knots.	154
3.119	Left Rotor Thrust Coefficient Versus Angle of Attack. I _N + 15°. Full Scale Airspeed 180 Knots.	155

Figure Number	<u>Title</u>	Page
3.120	Left Rotor Power Coefficient Versus Angle of Attack. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	156
3.121	Left Rotor Normal Force Coefficient Versus Angle of Attack. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	157
3.122	Left Rotor Side Force Coefficient Versus Angle of Attack. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	158
3.123	Left Rotor Pitching Moment Versus Angle of Attack. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	159
3.124	Left Rotor Yawing Moment Versus Angle of Attack. I _N = 15°. Full Scale Airspeed 180 Knots.	160
3.125	Left Rotor Thrust Coefficient Versus Angle ${\scriptstyle \sim}$ Degrees. I = 15°. Full Scale Airspeed 180 Knots.	161
3.126	Left Rotor Power Coefficient Versus Yaw Angle ${\scriptstyle \sim}$ Degrees. I = 15°. Full Scale Airspeed 180 Knots.	162
3.127	Left Rotor Normal Force Coefficient Versus Yaw Angle $_{\sim}$ Degrees. I $_{ m N}$ = 15°. Full Scale Airspeed 180 Knots.	163
3.128	Left Rotor Side Force Coefficient Versus Yaw Angle $_{^{\circ}}$ Degrees. I $_{_{N}}$ = 15°. Full Scale Airspeed 180 Knots.	164
3.129	Left Rotor Pitching Moment Versus Yaw Angle \sim Degrees. I = 15°. Full Scale Airspeed 180 Knots.	165
3.130	Left Rotor Yawing Moment Versus Yaw Angle \sim Degrees. I $_{ m N}$ = 15°. Full Scale Airspeed 180 Knots.	166
3.131	Left Rotor Thrust Coefficient Versus Rotor RPM. I $_{ m N}$ = 15°. Full Scale Airspeed 180 Knots.	167
3.132	Left Rotor Power Coefficient Versus Rotor RPM. I = 15°. Full Scale Airspeed	168

Figure Number	<u>Title</u>	Page
3.133	Left Rotor Normal Force Coefficient Versus Rotor RPM. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	169
3.134	Left Rotor Side Force Coefficient Versus Rotor RPM. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Krots.	170
3.135	Left Rotor Pitching Moment Coefficient Versus Rotor RPM. $I_N = 15^{\circ}$. Full Scale Airspeed 180 Knots.	171
A-1.	Comparison of Measured and Calculated Sideforce Coefficients using the Regression Technique.	A∸3
A-2.	Comparison of Measured and Calculated Normal Force Coefficients using the Regression Method.	A-4
A-3.	Variations of Coefficients in the Normal Force Equation with $\mu \text{Cos}\alpha$.	A-5
B-1.	Definition of Axes Systems and Quantities used in the Analysis.	B-3
B-2.	Thrust Coefficient versus Collective Comparison.	B-21
B-3.	Predicted and Measured Thrust Power Relationship during Shaft Angle Sweep.	B-22
B-4.	Variation of Normal Force with Collective Pitch - Predicted vs. Test.	B-24
B-5.	Predicted and Measured Variations of Side- force with Collective Pitch.	B-25
B-6.	Comparison of Predicted and Measured Pitching Moments during Shaft Angle Sweeps.	B-26

Table	LIST OF TABLES	
Number	<u>Title</u>	Page
I	Configuration Tested	17-21
II	Coefficients for Thrust Coefficient Derivatives	22
III	Coefficients for Power Coefficient Derivatives	23
IV	Coefficients for Normal Force Coefficients	24
v	Coefficients for Sideforce Derivatives	25
VI	Coefficients for Pitching Moment Derivatives	26
VII	Coefficients for Yawing Moment Derivatives	27
VIII	Coefficients for Chord Bending Moment Derivatives	28
IX	Coefficients for Flap Bending Moment. Derivatives	29
x	Comparison of Aircraft Trim Conditions as Computed with the Present and Former Rotor Models.	30
ХI	Derivatives at 140 Kt, $i_N = 60^{\circ}$, $\delta_F = 0^{\circ}$, - Former Rotor Model	1د
XII	Derivatives at 140 Kt, $i_N = 60^{\circ}$, $\delta_F = 0^{\circ}$,- Present Rotor Model	32
XIII	Derivatives at 60 Kt, i_{N} = 75°, δ_{F} = 40°,-Former Rotor Model	33
XIV	Derivatives at 60 Kt, $i_N = 75^{\circ}$, $\delta_F = 40^{\circ}$,- Present Rotor Mcdel	34
B-1.	List of Runs in which Cyclic was Fixed	B-19
B-2.	List of Runs in which Cyclic was Varied	B-20

LIST OF SYMBOLS

A	Rotor disc area	m^2 (ft ²)
A	Lateral cyclic pitch	degrees
В	Longitudinal cyclic pitch	degrees
$c_{_{\mathbf{T}}}$	Rotor thrust coefficient, T/pAV _T ²	-
C _P	Rotor power coefficient, HPX550/pAF _T ³	-
C _{NF}	Rotor normal force coefficient, $NF/\rho AV_T^2$	-
c _{sf}	Rotor sideforce coefficient, $SF/\rho AV_T^2$	-
C _{PM}	Rotor pitching moment coefficient, $PM/\rho AV_T^2R$	-
CYM	Rotor yawing moment coefficient, $\text{YM/pAV}_{\text{T}}^{2}\text{R}$	-
$C_{\mathtt{BM}}$	Chordwise bending moment	Nm (in.lb)
HP	Rotor shaft horsepower	W (HP)
ı _N	Nacelle angle	degrees
NF	Rotor normal force	N (1b)
PM .	Rotor pitching moment	N.m (ft.1b)
R	Rotor radius	m (ft)
r	Blade radial station	m (ft)
SF	Rotor sideforce	N (1b)
T	Rotor thrust	N (1b)
v	Flight speed	m/s (ft/sec)
$v_{\mathbf{T}}$	Tip speed	m/s (ft/sec)
YM	Rotor yawing moment	N.m (ft.1b)
a _i	Coefficients in a power series	-
α	Angle of attack	degrees

LIST OF SYMBOLS (CONTINUED)

β	Sideslip angle	degrees
δ _F	Wing flap setting	degrees
θ	Aircraft pitch attitude	degrees
θ.75	Blade angle at 75% radius	degrees
μ	Rotor tip speed ratio, $ extstyle{V_{ extstyle{T}}}$	_
ψ	Rotor shaft sideslip angle	degrees
Ω	Rotor rotational speed	rad/sec

This report presents the results of a study whose principal objective was the development of a mathematical model of a hingeless rotor for a tilt-rotor aircraft by synthesizing a set of wind tunnel data obtained on a model of the rotor. A secondary objective was to incorporate this rotor math model into a real-time flight simulation model of a hingeless rotor XV-15 tilt rotor aircraft and determine the effects on the aircraft trim and stability as compared to a former model developed under a previous contract.

The wind tunnel data used in the synthesis was obtained on a 1/4.622 scale model of the Boeing Model 222 tilt rotor aircraft tested under an earlier phase of the contract. The test generated sufficient data to define the rotor behavior over the range of flight speeds anticipated for the modified XV-15 aircraft.

The study was aimed at developing a set of equations that (1) would represent the rotor behavior as determined by the wind tunnel test data, (2) could be evaluated rapidly by a computer so that the computation cycle time requirements of real-time piloted simulation would be met.

Two approaches to developing the math model equations were tried before the final method was selected. The first approach was to apply the techniques of statistical linear regression to the wind tunnel model rotor data. The second approach was to develop a simplified analytical model for the hingeless rotor, correlate the predictions of the analytical model with the measured data and then use the correlation functions with the analysis to yield corrected values. These approaches are presented as appendices.

The actual method adopted was to apply a systematic curvefitting procedure. The resulting equations together with an extensive set of graphs of the rotor derivatives as obtained from the test data are presented. Numerous plots of the math model results against the corresponding wind tunnel data are provided. These show that the math model equations reproduce the test data very well.

The equations for the rotor were programmed into a previously developed flight simulation math model of the hingeless rotor XV-15 and the effect on aircraft trim and stability observed. It was found that trim is about the same as that calculated with the former rotor math model. The aircraft control derivatives are sufficiently different, however, that control phasing and rescheduling are required in order to maximize control efficiency.

1.0 INTRODUCTION

In many applications of rotor technology, there arises a need to be able to compute rotor forces and moments rapidly and accurately. One such application is real-time flight simulation where the rotor effects must be updated at intervals of less than 60 milliseconds. Existing finite element programs or even modal programs which solve the blade dynamic equations cannot satisfy the requirement for fast computation. In addition, the accuracy of the answers is limited by the sophistication of the analytical model, greater accuracy demands more detailed modeling which increases computation time.

Data Bank

One solution that has been used extensively in the past is to construct a bank of experimental or, less desirably, analytically derived data. Values of rotor hub forces and moments are then obtained by a rapid search and interpolation procedure at specified values of the rotor flight parameters. While this approach may be faster than a purely analytical computation, the range of flight parameters over which the interpolation must take place (airspeed, collective, shaft angle of attack, tip speed, cyclic control) and the need, in some cases, for quadratic rather than linear interpolation, place large demands on data storage and retrieval.

Functional Representation

A more promising approach is to synthesize the data obtained from test or analysis into a set of equations for each variable. For example, it may be possible to develop an equation for rotor normal force involving basic parameters such as μ , θ ,75, α , A_1 , B_1 . The resulting equations may be lengthy and complex, involving products and trigonometric functions of the basic variables, nevertheless, they can provide a very rapid means of calculating the forces or moments. The data synthesis approach may also yield benefits beyond the rapid reproduction of the data, in that functional relationships of a general character may be recognized and may be useful in understanding the physical behavior of the rotor. A further advantage of having a set of equations to represent the rotor forces and moments is that the equations may be used to estimate the behavior of a similar but untested rotor, and provide guidance in the preparation of a cost-effective wind tunnel test plan. In fact, once the general form of the equations is established, the wind tunnel testing could be regarded as a calibration activity.

Previous Work

The functional synthesis approach was adopted during a recent study (Reference 1) which involved development of a mathematical model of the XV-15 aircraft with a hingeless rotor for piloted simulation. In this study, wind tunnel data on a full-scale hingeless rotor obtained under a previous phase of this contract (Reference 2) was reduced to a relatively simple set of equations. Gaps in the wind tunnel data resulting from pressure of time and limitations on the tunnel speed were filled by calculation.

Satisfactory experience with this functional model of the rotor led to the conclusion that it would be worthwhile proceeding to a more definitive and complete model based on the extensive data, reported in Reference 3, that was acquired by testing a 1/4.622 scale model of the same rotor. The development of this new functional representation and the definition of a broad general procedure for performing functional synthesis of rotor test data is the subject of the present report.

Present Studies

Three approaches were explored. The first was an attempt to apply multivariable linear regression techniques to the data. This was motivated by the need to process the large amount of data available in the shortest time. The attempt met with limited success and is described in Appendix A. One of the difficulties encountered using the regression method was in making the correct choice of regression variables. From the previous work it was known that functions like ucosa, μ^2 Crsina, etc. would be required. There are, of course, many possible combinations of functions of the basic variables that will yield a satisfactory correlation, and a large factor in the success of the regression technique is making the correct choice of functions. It was, therefore, concluded that theoretical guidance was required. A simplified theoretical analysis was then written to identify these functions. Later, the analysis was tried in a predictor-corrector technique wherein the theoretical predictions were to be correlated with the test data and a correlation function generated. This approach was not pursued when it became evident that the analysis did not correctly predict trends with advance ratio. Results of the analysis and the approach are included as Appendix B.

The approach finally adopted was to develop curve fit equations for the derivatives $\partial C_{NF}/\partial \alpha$, $\partial C_{NF}/\partial A_1$, etc. These were then used to reduce the data to a reference set of values of Cp, C_{NF}, C_{SF}, etc., that were dependent on thrust coefficient, advance ratio and angle of attack only. This dependence was then curve fitted. A full description of the approach to together with extensive correlations with test data is presented in Section 3.

2.0 DATA BASE

The data which forms the basis for the study reported herein was obtained during extensive tests of a 1/4.622 Froude-scale model of the Boeing Model 222 tilt rotor aircraft. The testing and results are reported fully in the four volumes composing Reference 3. A brief description of the test and the nature and extent of the data is provided in this section.

Figure 2.1 shows the tilt rotor model installed in the Boeing Vertol wind tunnel. The test was designed to provide force and moment data on both the airframe and rotor over the expected normal range of flight speeds and attitudes. Data was obtained at seventeen points in the flight spectrum as shown by Figure 2.2. At each of these points, variations were made in fuselage angle of attack, yaw angle, collective pitch, cyclic pitch, wing flap setting and rotor rpm.

The extend of the data is indicated by Table I, which presents a summary of the configurations tested. The selection of test points was made in such a way that a comprehensive set of data was obtained for all potential flight conditions from hover through transition to cruise flight at simulated speeds up to 300 knots. Rotor force and moment data on each rotor was obtained from nacelle-mounted balances. The blades were strain gauged to provide flap and chordwise bending moment information.

Data Inspection

Before beginning a synthesis of the data, the plotted results contained in the four volumes of Reference 3 were inspected in order to identify possible bad data points attributable to such effects as zero shifts. This process resulted in a decision to utilize the data measured on the left-hand rotor only since the right-hand rotor data was questionable in some areas due to strain gauge failures. The acceptable portions of the data on the right rotor were used, however, to cross check the behavior of the left-hand rotor.

Data points that were called into question were inspected further using the microfiched records of the balance force data. As a result of this, the data points were either retained or discarded. The good data points were then punched out on cards and read into a computer program for formating and analysis during the next processing step.

3.0 REDUCTION METHOD AND COMPARISON WITH TEST DATA

Rotor forces and moments (referred to axes fixed in the rotor) depend on seven independent parameters - collective pitch (0.75), lateral cyclic (A1), longitudinal cyclic (B1), shaft angle of attack (a), rotor sideslip angle (ψ), rotor rpm and airspeed. For data reduction purposes it was assumed that any of the force or moment coefficients could be represented by an equation of the form

$$C_{F} = C_{FR} + \frac{\partial CF}{\partial A_{1}} (A_{1} - A_{1 \text{ ref}}) + \frac{\partial CF}{\partial B_{1}} (B_{1} - B_{1 \text{ ref}}) + \frac{\partial CF}{\partial \alpha} (u - \alpha_{\text{ref}})$$

$$+ \frac{\partial C_{F}}{\partial \psi} \psi + \frac{\partial C_{F}}{\partial RPM} (RPM - RPM_{ref})$$
(1)

In this equation, C_{FR} is the value of the coefficient at reference values of cyclic, angle of attack and rpm. The reference values are the nominal values at which the rotor was first trimmed to minimum blade loads and then collective pitch varied. Thus the coefficient C_{FR} may be written

$$C_{F_R} = f(\theta_{75}, \mu \cos \alpha_{ref}, A_{l ref}, B_{l ref}, RPM_{ref})$$
 (2)

The variation of these nominal values with the effective rotor advance ratio, $\mu\cos\alpha$, are presented in Figures 3.1 and 3.2. Deviations from these reference conditions are then accounted for by the derivative terms.

In order to establish the derivatives $\partial C_F/\partial A_1$, etc, a run-by-run, data point-by data point inspection of the plots of Reference 3 was conducted. It was found that quite often shifts occurred in one or more of the parameters that were to be held constant. For example, Run 41 was a run in which lateral cyclic was varied with the rotor at 80° angle of attack and 80 knots airspeed. For the first six data points, the longitudinal cyclic (B_1) was held fixed at 5.0 degrees. However for data points 7 through 11, the value of B_1 jumped by 0.3 degrees. By carefully noting such shifts and by using only those data points that met the criteria for a derivative, it was found that a reasonably consistent set of derivatives could be obtained. The values of the derivatives were plotted against $u\cos a$ and curves hand-faired through the points. These curves were then fitted by a polynomial in $u\cos a$ of the form

$$\frac{3CF}{3X} = \sum a_{i} (\mu \cos \alpha)^{i}$$
 (3)

where X represents A_1 , E_1 , α , ψ and rpm. The values of these coefficients are listed in Tables II through IX. The variation of the derivatives with $\mu\cos\alpha$ are presented in Figures 3.3 through 3.38.

3.1 Determination of the Values of the Coefficients, $\mathtt{C}_{\mathtt{FR}}$

The equations for the derivatives, together with the reference values of cyclic, angle of attack and rpm obtained from Figures 3.1 and 3.2 were then used in Equation (1) to compute values for C_{FR} for those runs in which collective alone was varied. The expectation was that the C_{FR} could be a linear function of θ .75 or C_{TR} . Figures 3.39 through 3.44 present the results of this procedure and it can be seen that the expectation of linearity is confirmed.

The next step in the reduction process was to obtain a set of equations that would reproduce the behavior of $C_{\rm FR}$ vs $C_{\rm TR}$ at the different flight conditions, i.e. since

$$C_{FR} = C_{F0} + \frac{\partial C_{FR}}{\partial C_{TR}} \quad C_{TR}$$
 (4)

the dependence of C_{FQ} and $\partial C_{FR}/\partial C_{TL}$ on μ must be established.

The values of CF0 and $\partial C_{FR}/\partial C_{TR}$ were plotted against $\mu \sin \alpha$ since previous work indicated that the dependence would be of the form

$$C_{F0} = f (\mu \sin \alpha, \mu)$$

$$\frac{\partial C_{FR}}{\partial C_{TR}} = f (\mu \sin \alpha, \mu)$$

Figure 3.45 shows the result of this for the case of pitching moment at zero thrust, Cp_{M0} . It can be seen that there is insufficient data at fixed μ and different values of α to be able to establish the form of the functions. Various combinations of $\mu \sin \alpha$, $\mu \cos \alpha$ were tried in an attempt to obtain smooth variations of the Cp_0 and $\partial Cp_R/\partial Cp_R$ that would include all the data points. None was successful. The most satisfactory approach was to plot the data against μ , fair a line through those points that lay closest to the nominal shaft angle of attack schedule (Figure 3.1), and then fit an equation to the line. A typical result is shown in Figure 3.46. This process was repeated for all the rotor force and moment components.

3.2 Math Model Equations

The final equations for the rotor forces and moments are lengthy since they are combinations of polynomials in μ and μcos_{α} whose coefficients change depending on which portion of the range of μ or μcos_{α} the rotor is operating in. For this reason, the entire set of equations will not be presented here. The equations are given in the form of a small computer subroutine in Appendix C.

The general equation used to calculate the forces and moments is Equation (1) viz

$$C_{F} = C_{FR} + \frac{\partial CF}{\partial A_{1}} (A_{1} - A_{1 \text{ ref}}) + \frac{\partial CF}{\partial B_{1}} (B_{1} - B_{1 \text{ ref}}) + \frac{\partial CF}{\partial \alpha} (\alpha - \alpha_{\text{ref}})$$

$$+ \partial C_{F} / \partial \psi \psi + \partial C_{F} / \partial RPM (RPM - RPM_{\text{ref}})$$

where
$$C_{TR} = \frac{\partial C_{TR}}{\partial \theta_{175}} (\theta_{175} - \theta_{0})$$
 (5)

$$C_{PR} = C_{P} + \frac{\partial C_{PR}}{\partial C_{TR}} \quad C_{T}_{R}$$
 (6)

$$C_{NF_R} = C_{NF_0} + \frac{\partial C_{NFR}}{\partial C_{TR}} C_{TR}$$
 (7)

$$C_{SF_{R}} = C_{SF_{0}} + \frac{\partial C_{SFR}}{\partial C_{TR}}$$
 (8)

$$C_{PM_{R}} = C_{PM_{0}} + \frac{\partial C_{PMR}}{\partial C_{TR}} C_{TR}$$
 (9)

$$C_{YM_R} = C_{YM_0} + \frac{\partial C_{YMR}}{\partial C_{TR}} C_{TR}$$
 (10)

in which the quantities $\partial C_{TR}/\partial \theta$, 75,00, C_{P0} , $\partial C_{PR}/\partial C_{TR}$, etc, are obtained from piecewise curve fit equations with μ or $\mu\cos\alpha$ as argument. The derivatives, $\partial C_{T}/\partial A_{1}$, $\partial C_{NF}/\partial B_{1}$, $\partial C_{PM}/\partial \alpha$, etc., are obtained from

$$\frac{\partial CF}{\partial X} = \sum_{i} a_{i} (\mu \cos \alpha)^{i}$$
 (11)

where the a_i are listed in Tables II through IX, and are furnished by the array X(I,J,K) in the subroutine.

The equations that define the reference quantities α_{ref} , A_{lref} , B_{lref} and RPM_{ref} , presented in Figures 3-1 and 3-2, are:

$$\alpha_{\text{ref}} = 89.72 - 322.82 + 770.41z^2 - 1446.34z^3 + 1449.9z^4$$

$$- 545.115z^5 \tag{12}$$

where

 $Z = \mu \cos \alpha$

$$A_{lref} = B_{lref} = 5.0^{\circ}$$
 (13)

and the reference rpm is a function of nacelle angle, $\hat{\mathbf{1}}_{N}$,

$$RPM_{ref} = 1185$$
 $i_N > 45^\circ$
= 1185 - 7.89(45- i_N) $i_N < 45^\circ$

The calculation procedure is illustrated by the following example.

If $0<\mu\cos\alpha<.015$,

$$\frac{\partial C_{TR}}{\partial \theta} = (11.933z + 0.882)/1000$$

$$\theta_{0} = -1.5 + 106.667z$$

and equation (5) yields the reference thrust coefficient C_{TR} . Equation (11) is now used to calculate the derivatives and equations (12), (13) and (14) used to compute the reference quantities. The total thrust coefficient C_{T} is then calculated for the given values of cyclic, angle of attack, yaw angle, and rpm.

For the same range of $\mu\cos\alpha$ the power coefficient at zero thrust, C_{PO} is

$$C_{P0} = (.035 - 9.6672)/1000$$

and

$$\frac{\partial C_{PR}}{\partial C_{TR}} = .094 - .267Z$$

The total power coefficient is then obtained in the same way as thrust.

If $0 < \mu < .51$ the equation for normal force coefficient at zero thrust, $C_{\rm NFO}$, is

$$1000 \times C_{NF_0}^{NF_0} = -1.45 + 1.1164\mu + 46.159\mu^2 + 46.153\mu^3$$

$$-4118.75\mu^4 + 27714.8\mu^5 - 74786\mu^6 + 89304\mu^7$$

$$-39318\mu^8$$

and the gradient with thrust coefficient is given by

$$\frac{dC_{NFR}}{dC_{TR}} = -.0087 + 2.122\mu - 10.95\mu^{2} - 34.52\mu^{3} + 420\mu^{4}$$
$$-1043\mu^{5} + 520.8\mu^{6} + 1029\mu^{7} - 966\mu^{8}$$

Using these quantities in equation (7) the reference normal force coefficient is calculated and finally the total normal force obtained from equation (1). The same procedures are used to calculate sideforce, pitching moment and yawing moment.

3.3 Comparison with the Test Data

The equations described in 3.2 were used to generate estimated values for the left rotor forces and moments at all the conditions investigated during the entire wind tunnel test. An extensive series of plots of the estimated and actual forces and moments were then made.

3.3.1 Collective Sweeps

The first test of the ability of the equations to reproduce the test data is to see how well the forces obtained during collective sweeps are estimated, since this is the data which was the most difficult to collapse. Figures 3.47 through 3.52 present comparisons of estimated and test values of C_T , C_P , C_{NF} , C_{SF} , C_{PM} and C_{YM} , respectively. Thrust is estimated to within 10% of the measured thrust at the same value of collective pitch. The estimated variation of power coefficient with thrust coefficient is also satisfactory at all the test conditions with the exception of hover at high values of C_T (.013) where the estimate is about 9% too low. Normal force estimates are also acceptable bearing in mind that, unlike power and thrust, normal force is very sensitive to cyclic and the accuracy achieved depends on how well the values of

the cyclic derivatives are fitted. Similar remarks apply to the comparisons of estimated and actual values for sideforce, pitching moment and yawing moment.

3.3.2 <u>Detailed Comparisons at Points in the Transition</u> Corridor

Figures 3.53 through 3.135 present a detailed comparison of the estimates obtained from the math model equations with the test values at three points in a typical tilt rotor transition corridor:

- 1. Hover
- 2. 45 knots and 90 degrees nacelle angle
- 3. 180 knots and 15 degrees nacelle angle

The comparisons are presented in the form of copies of the original wind tunnel data plots with the estimated values superimposed.

In hover, Figures 3.53 to 3.70, the rotor response to lateral and longitudinal cyclic is estimated very well considering the degree of scatter that exists in the measured data. The behavior with collective is reproduced nearly exactly.

For the early transition test condition of 45 knots and 90 degrees nacelle angle, Figures 3.71 to 3.106, the estimated variation of the forces and moments with lateral cyclic, A1, is generally in good agreement while the response to longitudinal cyclic, B1, is in very good agreement with the exception that the estimated yawing moment is displaced from the measured values. The correct slope of yawing moment with B₁ is predicted correctly, however. The dependence of the forces and moments on θ 75 is estimated well, again with the observation that yawing moment is displaced. For those runs where shaft angle was varied, Figures 3.89 through 3.94, it can be seen that the math model shows a weak dependence on shaft angle, α . This is attributed to the use of the parameter $\mu\cos\alpha$ in the equations since $\mu\cos\alpha$ changes rapidly near α = 90 degrees. Comparison of the estimated and test behavior of the data during yaw angle sweeps shows that the effect of yaw angle is not correctly estimated for normal force and pitching moment. This defect is probably due to the derivative curve fit in this region. The effect of rpm changes is reproduced well.

Figures 3.107 through 3.135 present the comparisons for a high speed end of transition condition, 180 knots and 15 degrees nacelle angle. Response to longitudinal cyclic is estimated extremely well for thrust, normal force, sideforce, pitching moment and yawing moment. The response of power coefficient

to B_1 is too exaggerated, however. The angle of attack sensitivities are reproduced very well and predicted yaw angle effects are also satisfactory. The effect of rpm variations are less satisfactory for this condition.

From the comparisons presented here it is concluded that the curve fit equations reproduce the test data sufficiently accurately for simulation purposes. The incorporation of the equations into the simulation math model of Reference 1 and the results are discussed in the following section.

4.0 EFFECT ON AIRCRAFT TRIM AND STABILITY

The math model equations for the rotor described in Section 3.0 were incorporated in the simulation model of the hingeless rotor XV-15 aircraft. This simulation model is detailed in Reference 1. The new equations, in the form of the subroutine given in Appendix C, replace the set of equations described in that Reference. An exception is that the pitch and yaw rate derivatives were retained since the test data on which the new equations are based does not contain rate effects.

The new rotor equations yield the forces and moments in a set of axes fixed in the rotor rather than the wind axes system used in the former equations. Some existing transformations from wind to body axes were therefore eliminated and others added.

4.1 Comparison with the Former Rotor Model

The simulation math model incorporating the new rotor equations was used to assess the effect of the updated rotor representation on the trim and stability of the XV-15/hingeless rotor aircraft and to ascertain whether control schedule changes would be required. Tables x through XIV present comparisons of aircraft trim attitude and control settings required and derivatives at selected points in the transition corridor.

From Table X it can be seen that the introduction of the updated rotor representation does not substantially change the values of trim pitch attitude (θ), stick position (δ_B) or throttle setting (δ_{TH}). The values of lateral (A_1) and longitudinal (B_1) cyclic (referred to the classical wind axes) are changed, however. With the new rotor math model, approximately twice as much lateral cyclic is required and about half as much longitudinal cyclic. The total cyclic. $\sqrt{A_1^2 + B_1^2}$, is about the same with both rotor representations. The different cyclic requirements reflect the different sensitivities to cyclic and angle of attack given by the two models. Since the new rotor representation has been shown to be in very good agreement with the test data, a re-phasing of the cyclic inputs to maximize control force and moment is indicated.

Tables XI through XIV present preliminary comparisons of the aircraft derivatives obtained using the present and former rotor models. Because of the altered cyclic sensitivities some of the control derivatives are changed and the control system gains and schedules require reworking to provide acceptable flying qualities. The controls-fixed derivatives L_p , M_q , N_r , X_u , Y_v , Z_w , for the 60 knot, i_N = 75° condition

are comparable with the two models. The off-diagonal derivative, Y_p , side force due to roll rate, is changed in sign compared to the present model. The reason for this has not yet been established. For the 140 Kt, $i_N = 60^\circ$ case (Tables XI and XII), the principal derivatives L_p and Z_w differ from the former model. The source of these differences is yet to be uncovered but a preliminary examination indicates that the new model exhibits a higher sensitivity of thrust to combinations of angle of attack and effective rpm changes such as occur during rolling, than did the former model.

5.0. CONCLUSIONS AND RECOMMENDATIONS

The objective of the study was to develop a functional representation of a hingeless rotor based on extensive wind tunnel data and to incorporate this representation into a real-time simulation math model of a hingeless rotor XV-15. Changes in flying qualities caused by the new rotor representation were to be determined and noted.

Conclusions

- A mathematical representation of the rotor data was developed through a systematic curve-fitting approach. The results show that the curve-fit equations reproduce the wind tunnel data very well.
- 2. The rotor equations were incorporated into the simulation model. Preliminary evaluation of trim and derivative data show that cyclic rephasing is required in order to optimize the aircraft response to control. Stick-fixed behavior of the aircraft is generally comparable to that obtained using the former rotor representation.
- 3. Extensive plots of the rotor derivatives as functions of the effective advance ratio have been presented. These are of considerable value in themselves since they may be used to assess rotor behavior for similar configurations.
- 4. A curve-fit representation of the rotor, although lengthy, satisfies the computational speed requirements of real-time simulation just as well as the equations in a functional representation. This is because the functional representation, although simpler in form, involves computer evaluations of transcendental functions, e.g., Tan-1x, sina etc. which require as much time as the evaluation of polynomials in the curve-fit approach.
- 5. An attempt was made to automate the process of data synthesis using multivariable linear regression. In principle, if a sufficiently large number of candidate correlates are available to the regression algorithm then a successful synthesis should result. However, the likely correlates must be supplied to the computer and the selection of the correct correlates requires a considerable amount of skill, if not luck. The final equations produced by the regression, while they may fit the particular set of data used, are not necessarily of a general enough nature that they can be extended to other rotor configurations by simply altering constants in the equations.

Recommendations

- Probably the best overall approach to the problem of providing a fast, but general, algorithm for rotor representation in real-time simulation is to develop a simplified analysis whose predictions can be calibrated against wind tunnel data. These analytical predictions would then be operated on by the calibration functions to produce estimates of the rotor forces and moments. A step in this direction was made in this study but more work is required.
- 2. A further recommendation is that during the preparation of wind tunnel test run schedules, every effort should be made to select the runs so that the natural parameters of the rotor are systematically varied over a broad enough range that the data synthesis process is facilitated. For example, when testing at different rotor shaft angles at fixed airspeed, such as is required for transition corridor definition, it is desirable to do this at a series of fixed values of rotor rpm even though the aircraft will not necessarily operate at some of the rpm values. This will, however, ensure that data exists over a wide enough range of values of μ , $\mu \sin \alpha$, $\mu \cos \alpha$ that curves may be confidently drawn through points of constant $\mu \sin \alpha$, for example, and equations fitted to them,
- 3. The final recommendation arises from the difficulties experienced in extracting rotor derivatives from the test data. The wind tunnel run schedule was purposely designed to acquire rotor derivative data directly, by making runs in which one control at a time was varied while the others were fixed.

Unfortunately, during many of the runs, shifts in cyclic, collective pitch or shaft angle occurred. This made the job of extracting rotor derivatives very laborious since each point had to be inspected to make sure that the fixed controls had actually remained fixed during the run. It is therefore recommended that in future tests of this nature every effort should be made to ensure that the control settings remain at the desired levels. This may require the use of more complex and more accurate rotor control systems than the simple position-feedback system used in this test.

6.0 REFERENCES

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TESTED
CONFIGURATIONS
H.
TABLE

		•					TEST	VARIABLES	NLES HI	HELD CONSTANT	TANT					
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TABLE I. CONFIGURATIONS TESTED (Continued)

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VARTABLES	749	30.0 30.0 30.0 30.0	33.0 33.0 33.0 33.0	30.0 30.0 30.0 30.0	19.5 19.5 19.5 19.5
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	FIGURES	1-24 25-40 49-7. 71-96 97-120 121-144 145-168	1-24 25-46 49-72 71-96 97-120 121-144 145-168	. 1-24 25-48 49-72 71-96 97-120 121-144	25-48 49-72 71-96 97-129 121-154
	PARAMETER	TAM PAGE LONG. CYC. LAT. CYC. 5.75 Friab	TAM AMOLE LOMG. CTC. LAT. CTC. 73 4:18 RELAP	TAM AMOLE LONG. CTC. LAT. CTC. 8.75 Fr.AP	TAM AMOLE LONG. CTC. LAT. CTC. 6.75 FILM
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TABLE 1. CONFIGURATIONS TESTED (Continued)

TABLE I. CONFIGURAT.ONS TESTED (Continued)

							TES	T VARIA	BLES H	TEST VARIABLES HELD CONSTANT	TANT					
CONDITION	PARAMETER Varied	FIGURES	>	สรณ์ ช	NI	RPM .	⁷ ςι _θ	T _V	B ₁ L	o de Li	975R	A1R	BlR	o ye	•	DATA
CRUISE In = -1.	88	1-24	259 259		-1.4	827	52.1 52.1	üü	1:1	i. 0.	53.2	00	e	5.3	-:-:	2 -
VFS - 260 KTS	YAW ANGLE LONG. CYC.	25-48-	259	••	-1.5	628 829	51.9	٠. د.	e:	7.7	53.2	••	e:-	7.	~	
	LAT. CYC.	97,98,100,101,259	259		21.5	827	51.6		-1.0		53.2	0	**	<u></u>		
CRUISE		1-24	299		-1.5	827	56.2	-	75.		57.0	36			: -	-]:
IN1.	YAN ANGLE LONG. CYC.	25-48	299	••	77	827	56.4		aj I		57.9	35.5	27	:	: 0	:-
	LAT. CYC.	64 -87 88,89,91,92 88-93	299 299 299	•	45.5	825 827 827	56.0	·	B 75	-1.5	57.9	.35	27		٥٠.	
	ı		1		-		}		_		-	_		•	:	_

Table II. Coefficients for Thrust Coefficient Derivatives

į	le	2	£,	Pe	S _e	ş	4	8
ac _T /aA₁	3CT/3A1 -(.45062 (0)-(.4	-(.47681 01	7E8F 01 -0.2745E 03	C.1200E 04	0.1200E 04 -0.1752E 04	1	0.9966E 03 -0.1652E 03	0.0000E 00
9C _T /∂8₁	3CT/381 -(.1416E 60 -0.5	-v.5737E 02		0.2480E 03 -0.4604E 03	1	0.3999E 03 -0.1319E 03	0.0000E 00	0.0000E 00
əC⊤/∂α	-0.7110e-C1	c.1	453E 03 -0.1733E 04		0.8800E C4 -0.2198E 05		0.2950E 05 -0.1849E 05	0.4753E U4
эс_1/э∳	1.0000E CO	00 30000°0	00 3000°n	0.0000E 00	l	0.0000E 00 0.0000E 00	0.0000E 00	0.0000E 00
∂C _T /∂RPM	OCT/BRPM C.LOUDE CO	00 300%6*0	C.000CE 00	0.0000E 00	0.0000E 00	0.0000E 00	0.0000E 00	0.0000E 00

Table III. Coefficients for Power Coefficient Derivatives

									1
	le.	2	ક્ર	94	g.	9e	Le	8 _e	
acp/aA1	acp/aA1 −u.zzuE−u1		v.1495E U1 -6.210cE G2	20 34502*0		0°.0000€ 00 0°.0000€ 00	O-CCCUE OC	00 30000°0	2
ЭС _Р /3В ₁		L.2070E-v1 -4.2693F C1 0.655GE C0 -0.1486E 02	U.855UE UU	-0.1486E 02		0.1711E 02 0.0000E 00 0.0000E 00 0.0000E 00	0.C000E 00	0.0000£ 00	
эСρ/дα	v.11665-61	U.1651E UL		0.3814E 02	U.a509E UI 0.3814E 02 -U.22C3E 03 0.2877E 03 -0.115bE 63	0.2877E 03	-0.115bE 63	ם•ספפרב ספ	.3
ðCp/∂∜		0.0030z 00 (.uuruf 00	חיחחתכב חי	0.0000E 00	U. 3000E 00	O. OOOCE CO	00 30000*0	0.00cck uu	
аср/а пр м	-0-97006-0-	-6.7646E-62	00 30+68 • 0	U.GUUUE 00	3Cp/appm -0.9700E-(s -6.764CE-G2 6.894CE 00 0.600UE 00 0.6000E 00 0.60CCE 00 0.6CCCE 00	0.0000E GO	0.0CCCE GO	O.COCUE OC	

Table IV. Coefficients for Normal Force Derivatives

		82	2	Pe	ð.	မှု	6	&
acne/aa,	3CNF/3A1 -C.1371E 01	0.1	690E 020.2104E 03	0.5176E 03	0.5176E 03 -0.5038E 03	0.1773E 03	0.0000E 00	0.0000E 00
ac _{NF} /∂B₁	3CNF/3B1 -0.1422E C1		6.5147E 01 -6.2742F 02	0.0000E 00	0.0000E 00 0.0000E 00	0.0000E 00	0.0000E 00	0.0000E 00
∂CNF/ðà	C.2852E 00 -6.7	-6.750žE 01	C-3427E 02	0.00000	0.0000E 00 0.0000E 00	0.0000E 00	0° 00000 0° 00000 0°	0°0000E 00
∂C _{NF} /∂¢	C. c O 3 0 = - 6 1	1.2	633E 01 -0.2825E 02	0.4968F G2	0.4968E G2 -0.1105E 02	0.0000E 00	0.0000€	0.0000E 00
³ CNF/ ³ RPM	OCNE/ORPM C-16CCE-U3	0.2	342E-01 -6.1129E 01 0.1712E 01 -0.7423E 00	0.1712E 01	-0.7423E 00	0.0000E 00 0.0000E 00 0.0000E 00	0.0000£ 00	0.0000E 00

Table V. Coefficients for Sideforce Derivatives.

		2	£	84	g,	မွ	Le	æ
∂C _{SF} /∂A₁	0.7213E 00 0.1064E	0.10645 02	02 -0.1761E 03	0.6883E 03	0.6883E 03 -6.8232E 03	0.3206E 63	0.00006 00	0.000UE 0C
∂C _S F/∂B ₁	3CSF/381 -6.1252k 61	C.1765E	01 -C.4897E 02	i	0.6304E 02 -0.2846E 02 0.0000E 00	0.0000E 00	0.0000E 00 0.0000E 00	Q.0000E UU
∂CSF/ða	3CSF/3α -0.11 rue-01 -0.55 45E		ul 6.7841E 02 -0.1572E 03 0.7496E 02 0.0000E 00 0.0000E 00 0.0000E 00	-0.1572E 03	0.74965 02	0.0000E 60	0.0000E 00	0.00CUE UL
ðCSF/ð∳	U.1416E UU -U.50636	-6.5063E 01		0.3399E 62 -0.1630E 62	0.0000E 00	0 -0000E 00	0.0000E 0U	O.UJUVE UU
∂CSF/∂RPM	C.550UE-03	-0.12196-61	0CSF/0RPM C.550UE-03 -U.1219E-01 -0.527UE 01	0.4619E 02	0.4619E 02 -6.1262E 03 0.1411E 03 -0.5569E 02	0.14116 03	-0.5569E 02	0.3000£ uu

Table VI. Coefficients for Pitching Moment Derivatives

•								
	1.		٠ •	. 78	¥°	9.	42	82
∂CpW/∂A1	-C.9261E 00	3CpW/3A1 -C.9261E 00 -6.1969E 02	L	0.1161E 03 -0.1508E 03	0.6084E 02		0.0000E 00 0.0000E 00 0.0000E 00	0.0000E 00
aCpM/3B1	-0.3212E 01	-0.5118E 01	3CPN/381 -0.3212E 01 -0.5118E 01 -0.1174E 02		0.4390E 02 -0.2674E 02	0.0000E 00	0.0000E 00	0.0000E 00
эс/М/да	0.3494E 00		0.4544E 01 -6.7210E 01		0.0000E 00 0.0000E 00	0 -0000E 00	0.0000E 00	0.0000E 00
¢e/₩dge		0.5250E-01 -0.2972E 01		0.2979E 02 -0.3286E 02	0.1048E 02	0 -0000E 00	0.0000E 00	0.0000E 0U
^{SC} PM ^{/3} RPM	асрм/апрм -6.1000E-03 -0.	-0.9926E-01	9926E-01 0.1248E 00 -0.5549E-01	-0.5549E-01	0.0000E 00	0.0000È 00	0.0000E 00 0,0000E 00	O POOODE OO

Table VII. Coefficients for Yawing Moment Derivatives

	l _e	2	£	4	န္	မ္မ	47	æ
OCYM/OA1		C+3008E 01 -0.72c0E 00		0.6013E 02 -0.1995E 03		0.2035E 63 -0.7061E 02	0.0000£ 00	0.0000E UG
aCyM/3B₁	6. 37117e CO	3CYM/3B1 -C.91176 CO -C.1735E 02		0.1066£ 03 -0.1226E 03	0.4007E 02	0.0000E 00 0.0000E 00	0 -0000E 00	0.0000E 00
∂Сγ м /∂α	0.5790E-01	0.5796E-01	-0.5661E 02		0.6781E 02 -0.2567E 02	0.0000E 00	0.0000E 00	0.0000E 0
aCym/a¢	U.1063E GO		0.5334E 61 -0.1209E 62	0.2367E 01	0-0000E CO	0.0000E 00	0 •0000E 00	0.0000E 00
OCYM/BRPM	C.5263E-63	0.1724E 0C	0.1724E UC -C.7342E OC	0.1638£ 01	0.1638E 01 -0.1733E 01	0.67885 00	0.0000£ 00	0.000uE CO

Table VIII. Coefficients for Chord Bending Moment Derivative

	-	2	ŗ	*	ħ.	ş	87	8
ac _{BM} /∂A₁	(.21e5f 62	C.8657E U2	3CBM/3A1 (.2165F L2 C.8097E U2 -L.1026E U2 -0.3775E 03	-0.3775E 03	0.3345E 03	0.0000E 00	0.00000 00	00.00
^{3C} BM/3B₁	3CBIN/381 (-2294E UZ	50 534E+*0		U.Zo71E 03 -U.Z580E 03	0.0000000	0.6000E 00		0.0000E 00 0.000UE 00
∂CβM/∂α	3CB14/3a (+218ce 01		0.4C14E 02 C.COUCE 00	U.000UE 00	0.00000.0	0.000UUE 00 0.0000E 00 0.0000E 00	0.0000E 00	0.0000£ 00
A€/MBJe	10-3005-0 46/MB26	C.483hE G2	C.*83hE G2 -C.9337E 02	U.3934E 03 -0.6262E 03 0.2932E 03 0.0000E 00 0.0000E 00	-0.6242E 03	0.2932E 03	0.0000E 00	0.0000E 00
3CBM/3RPM	OCBIN/ORPIN C.UGGEE CO	0. ECUOE UO	1	0.0000E 00 0.0000E 00	0.0000E 00	0.0000E 00	00.000 00 00.0000 00.0000 00.000 00.000 00.000 00.000 00.000 00.000 00.000 00.000 00.0	040000E 00
							_	

Table IX. Coefficients for Flap Bending Moment Derivative

	1.	2	r,	76	្ណួ	g _e	Le	80
∂FBM/∂A₁		V**796E UI	0.c7242 (1		6.4634E 63 -6.3272E 03	0.6000E 00	0.0000E 00	0.00000
åFBM/∂B₁	C.3385E UI	C.1043E 63	C.1043E 63 -0.8547E 03	0.2364£ 04	0.2364£ 04 -0.2458£ 04 0.9075£ 03 0.0060E 00	0.9075E 03	0.00COE 00	0.0000E 0G
θF _{BM} /θα	U.1252E 01	50 3848£-0	U.1252E 01 U.3943E UZ -U.3031E G3	6.0403E 03		0.4470€ 03	0.000ce 00	0.000uce 0u
∂F8M/∂ψ	aFgM/a⊬ -u.≥ulu∈-ul	L.0026E	UI -C.2384E U2	U.8U2E£ 02	U.8U26£ 02 -0.3817£ 02	0.0000E 00	0.000000	0.0000t 00
FBM/9RPM	נייחטרב סס	იი ვიეგი•ი	U.0000E UU	00 3000000	U.0000E GO G.0000E OG	C.0000E 0C	0.00C0E 00	0.0000E CC

	FORMER ROTOR MODEL	PRESENT ROTOR MODEL								
θ.75	10.2 F	9.7 P	8.26	7.42	18.49	15.06	24.8	24.4	41.7	44.1
В	.11	0	2.71	1.94	5.42	2.99	4.00	1.73	2.30	1.67
A ₁	06	01	-1.46	-3.23	-3.13	-5.26	-1.90	-3.05	71	-1.87
⁶ тн	5.87	5.36	3.5	3.3	5.5	5.04	3.85	3.60	2.67	2.70
e B	07	0	69.	.24	-1.56	-1.41	60	92	60	.5
θ	1.16	1.04	80.8	7.23	44	.27	5.14	3.39	3.08	3.3
o F		• •	•	· •	,	<u>.</u>	(;	(; >
Z	3	.06	ľ	ċ				20.	(· >
VKT	(O	(140.		140.	000	7007

COMPARISON OF AIRCRAFT TRIM CONDITIONS AS COMPUTED WITH THE PRESENT AND FORMER ROTCR MODELS TABLE X.

	X V = 15	STABILITY	STABILITY AND CONTROL DERIVATIVES	ERIVATIV	ES		
	G.W. = 1356 C.G. =	13564.15 LBS	VEL. = 140.00 R/C =01	0.00 KTS	ALT. #	.00 59.00	FT Deg
	L/1XX	M/IYY	N/122	E X	¥/ >	2	H/2
DFLA	0000	1.4122	0000•	3917	0000•	•	+996•
DFLS	0/64.	•0059	• 1331	0103	3151	•	.3319
OFLR	0778	.0588	.2436	0632	0969••	•	0191
THEOM	0000-	••0001	0000•	9000.	0000.	•	.0013
۵	6006.1.	.0013	5984	++60	.7793	.	•0556
o	0000	-5.0223	9400	9484.	0000.	-2.3391	1391
œ	096***	•.0243	-17852	•0126	2.0453	•	0150
Þ	0000	,0135	0000	•1413	0000	•	0767
>	••6115	.0043	•0083	9200	2198		•0118
3	0000	0051	0000•	+0724	0000.	1///	*•666R
INACL	0700-	••0001	(mg 0.	0008	0000-	•	.0013

- PORMER ROTOR MODEL. DERIVATIVES AT 140 KT, $i_N = 60^{\circ}$, $\delta_F = 0^{\circ}$, TABLE XI.

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XV	STABILITY	STABILITY AND CANTROL DERIVATIVES	DERIVATIVI	S	
G.W. = 13564.15 C.G. = .16	.4.15 18S	VEL. = 14 R/C =	140.06 KTS	ALT. :: TEMP =	.00 FT 59.00 DFG
L/1XX	H/1YY	N/127	X/X	¥ / ¥	Z/H
0000.	1.5118	0 .00.	.1760	0000.	.2172
1656.	• 0095	•0366	• 0058	1757	.2805
5170	• 0019	.0701	0188	•2·3158	•0020
0000-	0000.	0000	0005	00000-	.0011
1461.6	1200-	8557	0458	1.5398	-1152
00000	-5-3254	•0042	.2313	0000	-2.1627
7579	1445	11.1.	-0182	3.1010	9690•
0000-	.0252	0000	••0564	0000	1.2231
nox1	.0050	•0656	- 0000	1762	• 00#3
0000-	0168	•0000	0367	••0000	*************************************
0000-	0000	0000	5070.	00000-	.001

= 0 - PRESENT ROTOR MODEL. DERIVATIVES AT 140 KT, i_N = 60°, δ_P TABLE XII.

	XV=15	STABILITY	ONV	CANTROL DERIVATIVES	ES	
	G.W. = 13564.15 C.G. = .01	4.15 185 .01 1N	VFL. # R/C #	60.00 KTS	ALT	.00 FT 59.00 DFG
	L/1XX	HZIYY	N/122	X/X	X / X	И/2
0F! B	0000.	.7450	0000	+612	0000•	.1432
DFLS	.3433	0042	.0541	• 0079	-1679	.1530
DFLR	111000	+100+	• 0945	0163	2686	0139
THEON	0000	• 0001	0000-	• 0005	0000•	0028
Q.	-1.4362	• 0086	9+3C+2	• 0349	3427	1.080
a	0700.	-3.0395	•00•3	.2876	00000	-1.2513
α	1652	0147	-1385	•0187	6090•	1117
5	0000-	.0230	0000	5750.	0000	-1075
>	n107	.0040	0021	••0100	r686	6400
3	0000	.0100	0000••	1237	00000	
INACL	0000-	.0001	0000	9000•	0000∙	\$E00*-

TAULE XIII. DERIVATIVES AT 60 KT, i $_{
m N}$ = 75°, $^6
m_F$ = 40° - Pormer rotor model.

	XV-15	STABILITY	STABILITY AND CONTROL DE L'ANTIVES	DE HVATIV	ES		
	G.W. = 13564.15 C.G. = .01	.4.15 LBS	VEL	60.90 KTS	ALT. = TEMP =	.00	FT DFG
	•	•		:			
	(X	44I/H	771/N	×	¥.`,	2	H/2
0F1 A	0000-	.8951	000 0 •	- 5418	•• 0000		3302
0F1 S	. 1018	••0008	* 0 * 0• .	•0193	-+4890	c	.0711
0F! A	- 2382	6000.	.5960	0166	-1.0588	Ċ	0088
THEBY	0000.	0000.	J000-	*000 •	0600•	•	0020
۵.	1.7.181	2200.	**5635	0105	.4723	Ċ	0302
3	00000	-3·000g	• 00 •	.2442	0000.	-1.3504	5n4
α	2045	•.0159	1961.	•0100	.1634	0797	797
ם	0000.	.0116	90 00 -	0473	0000	Č	0623
>		.0050	***	•000	2450	· /	•0035
3	0000	.0105	.000.	• 0955	0000-	-16283	283
INACL	0000.	0000	•••	+000	0000•	/ č	0200-

= 40°+ PRESENT ROTOR MODEL. TABLE XIV. DERIVATIVES AT 60 KT, in

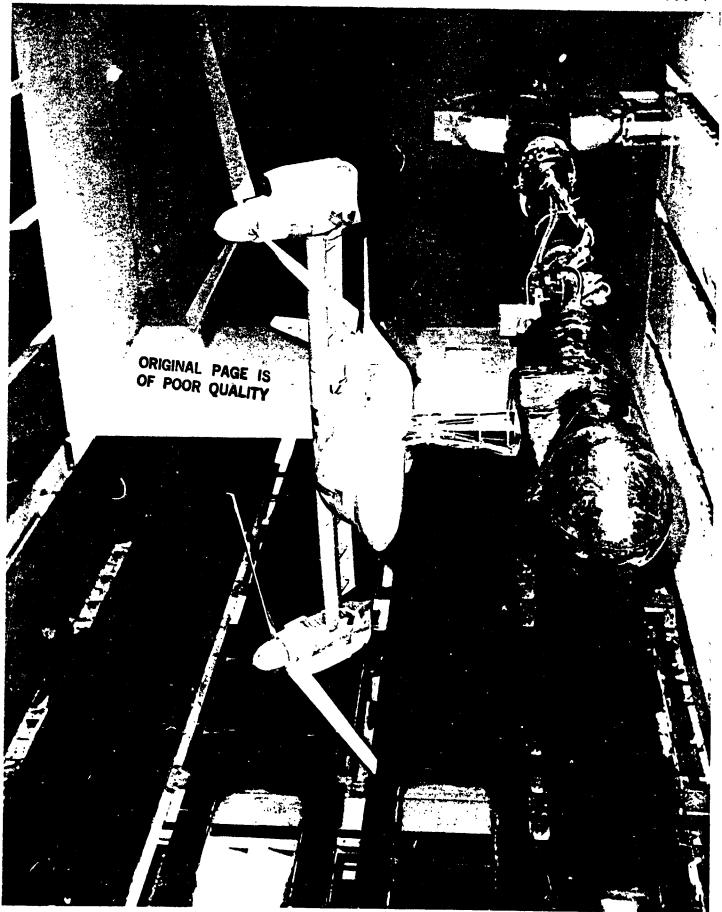
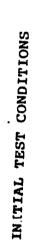


Figure 2.1. 1/4.622 Scale Model Installed in the Wind Tunnel Test Section



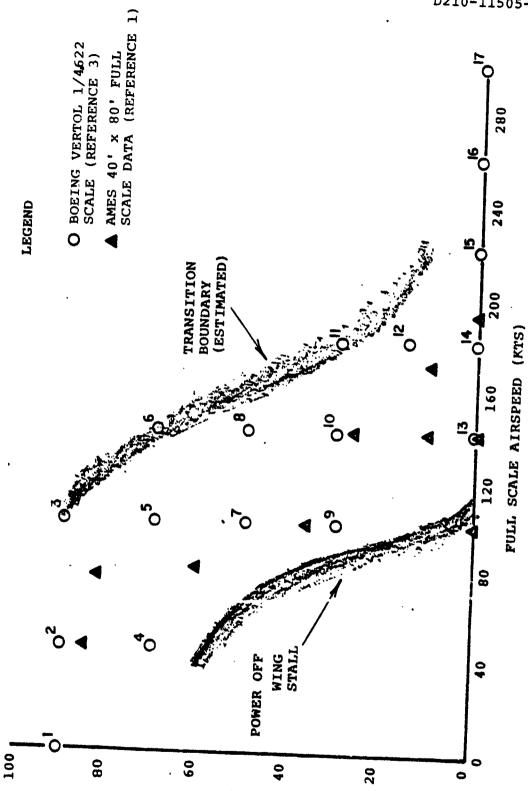


Figure 2.2. Scope of Test of Reference 3

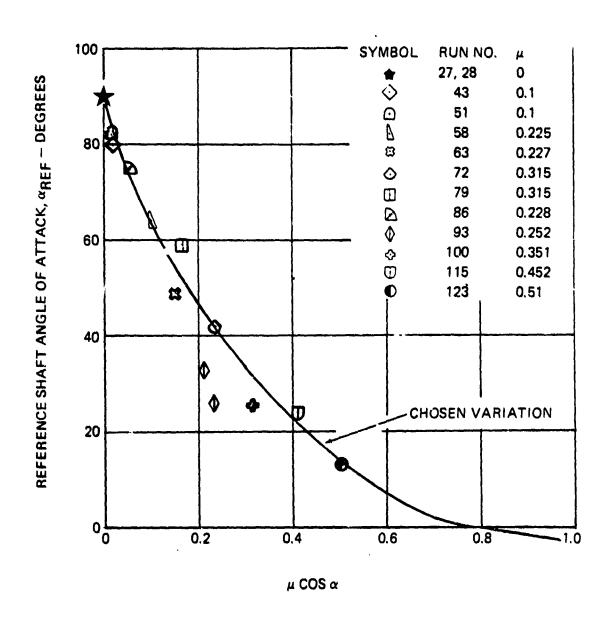


Figure 3.1. Variation of Reference Angle of Attack With μ Cos α

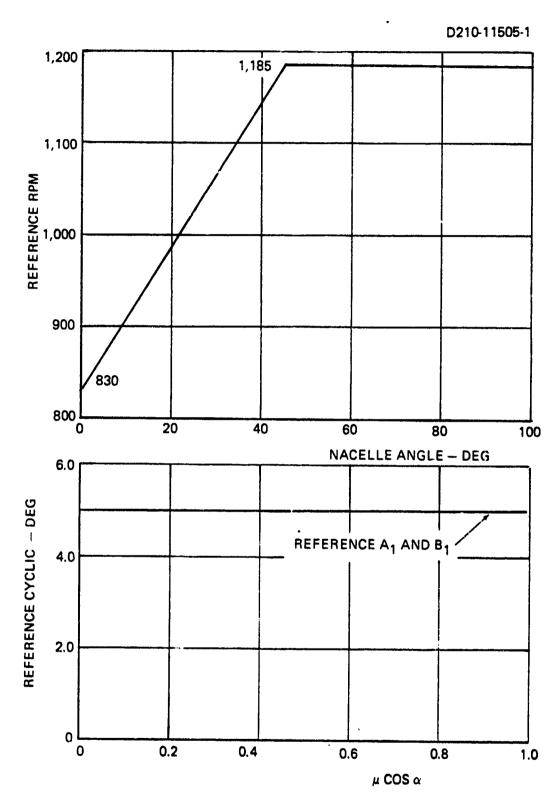
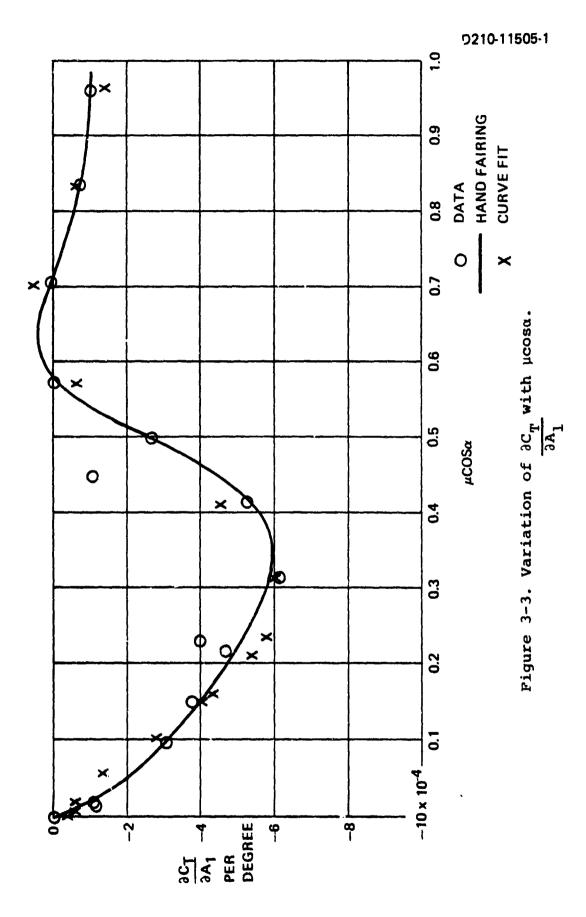


Figure 3.2. Definition of Reference Values of Cyclic and RPM



The state of the s

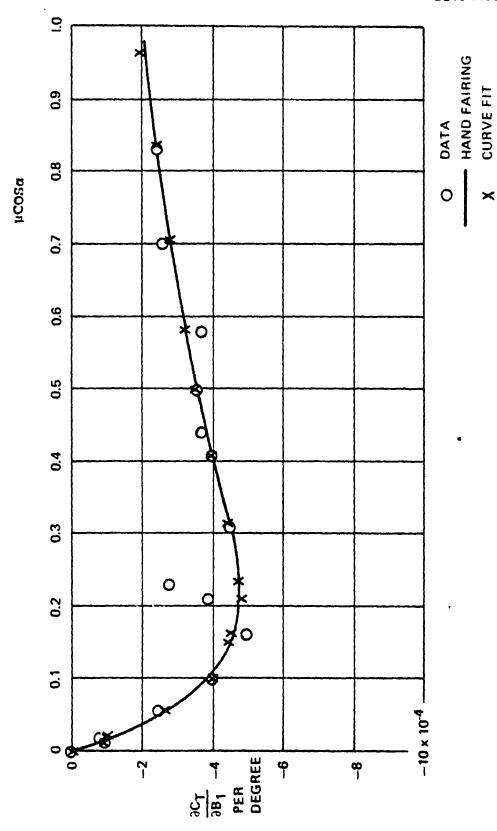


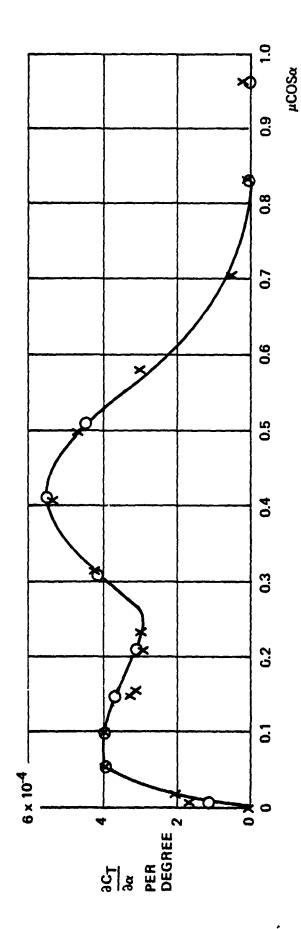
Figure 3-4. Variation of $\frac{\partial C_T}{\partial B_1}$ with $\mu COS\alpha$.



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Figure 3-5. Variation of $3C_T$ with $\mu\cos\alpha$.

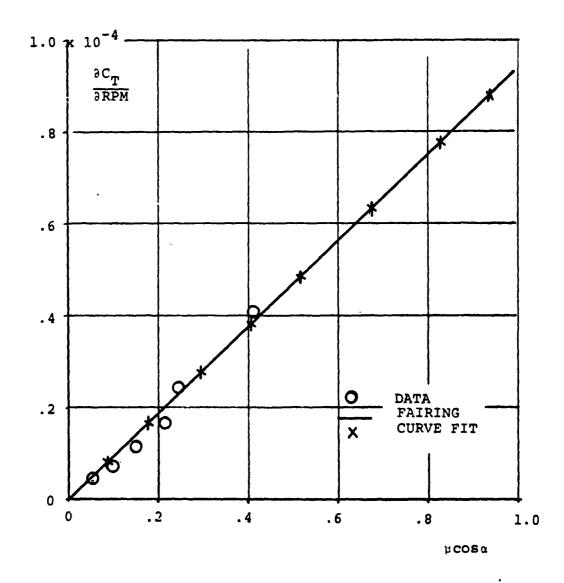


Figure 3.6. Variation of $\partial C_{\mathbf{T}}/\partial RPM$ with $\mu \cos\alpha$.

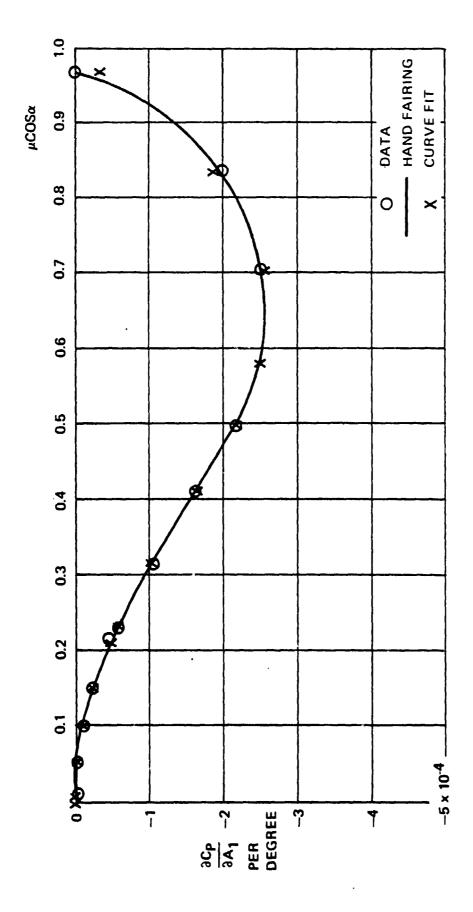


Figure 3-7. Variation of $\frac{\partial C_p}{\partial A_1}$ with $\mu\cos\alpha$.

CURVE FIT

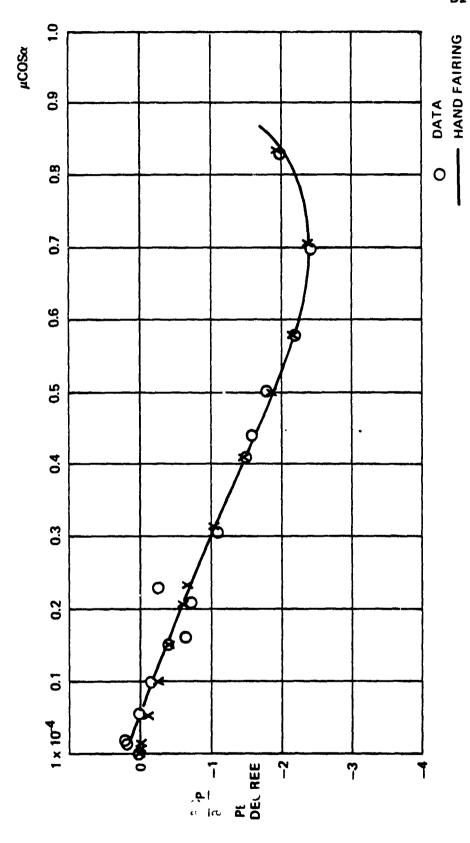
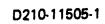
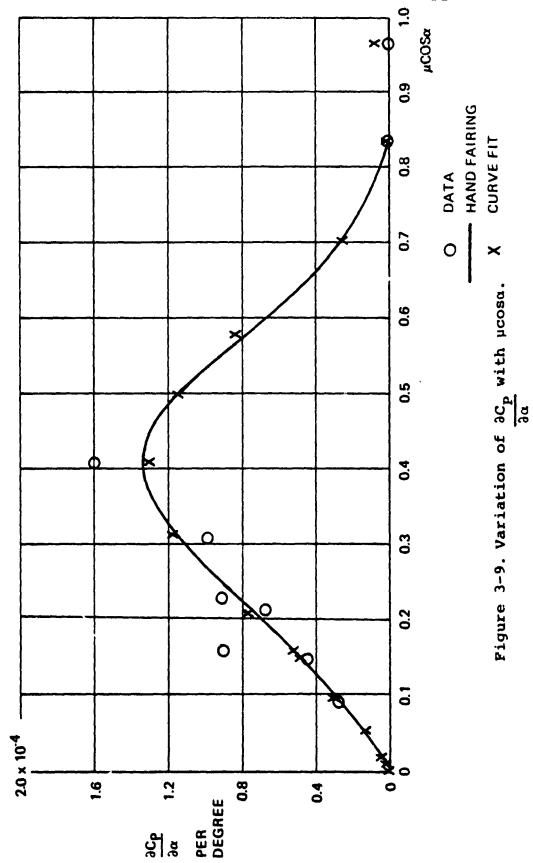


Figure 3-8. Variation of $\frac{\partial C_p}{\partial B_1}$ with $\mu \cos \alpha$.





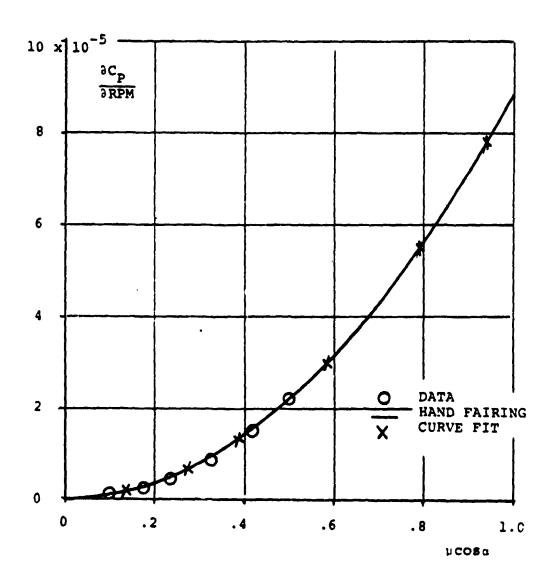


Figure 3.10. Variation of $\partial C_p/\partial RPM$ with $\mu\cos\alpha$.



CURVE FIT

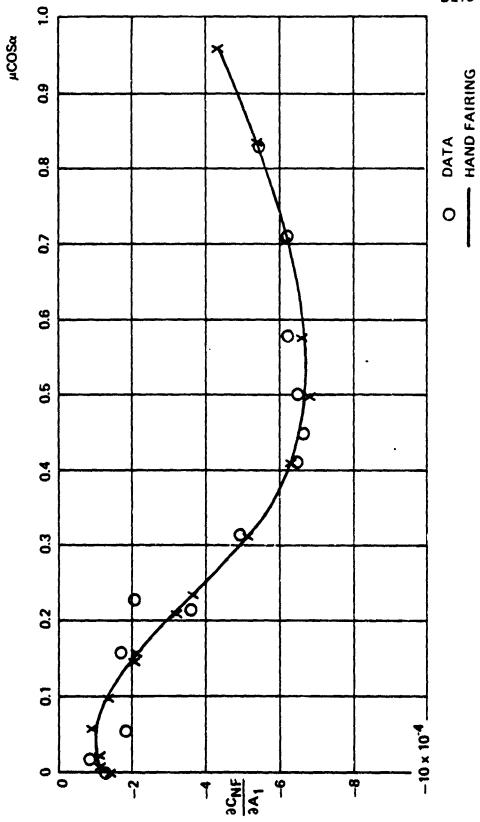
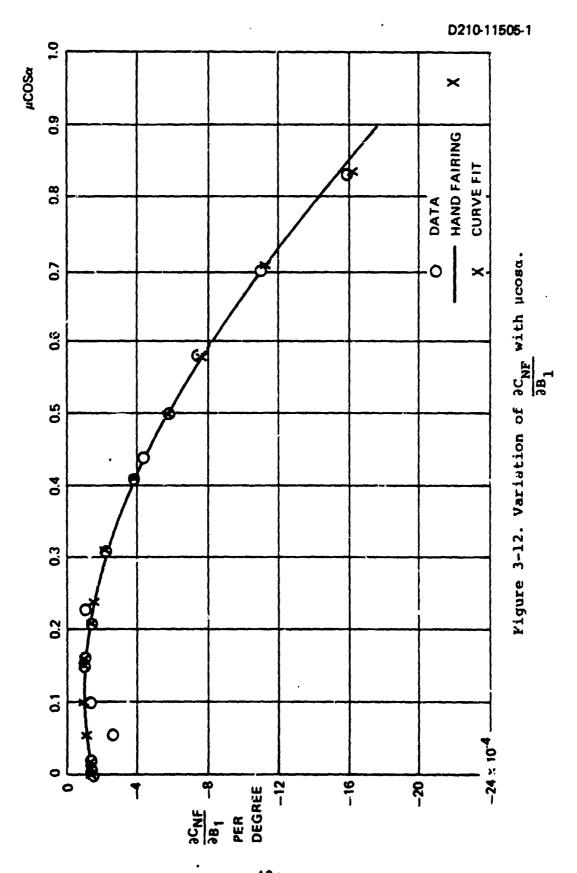
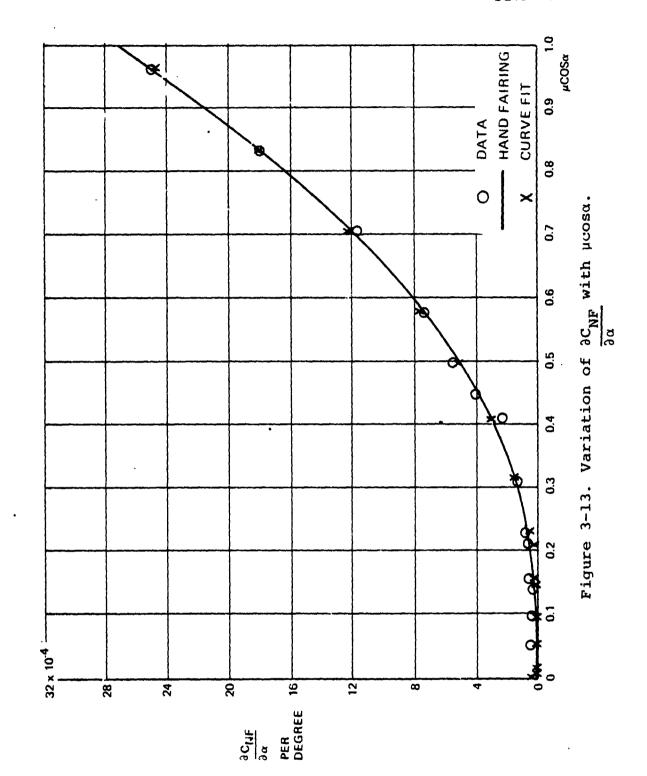
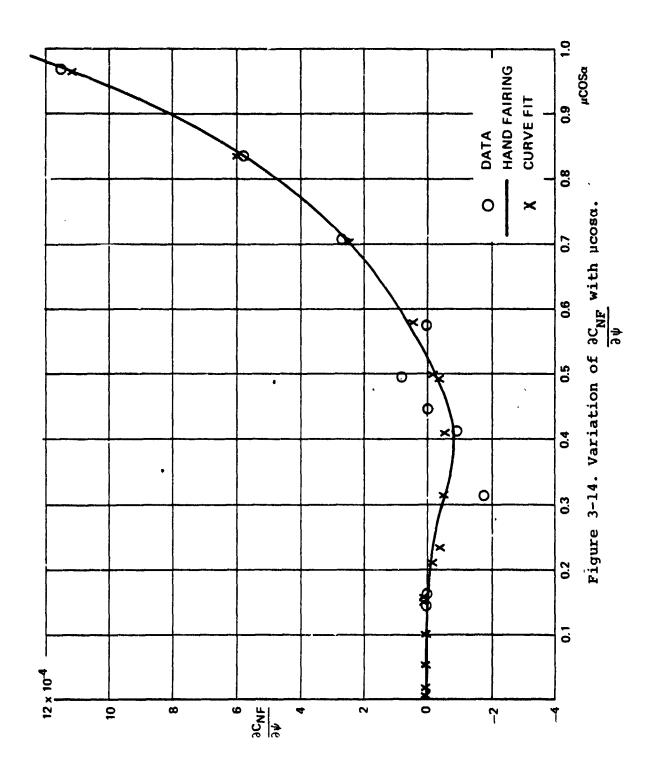
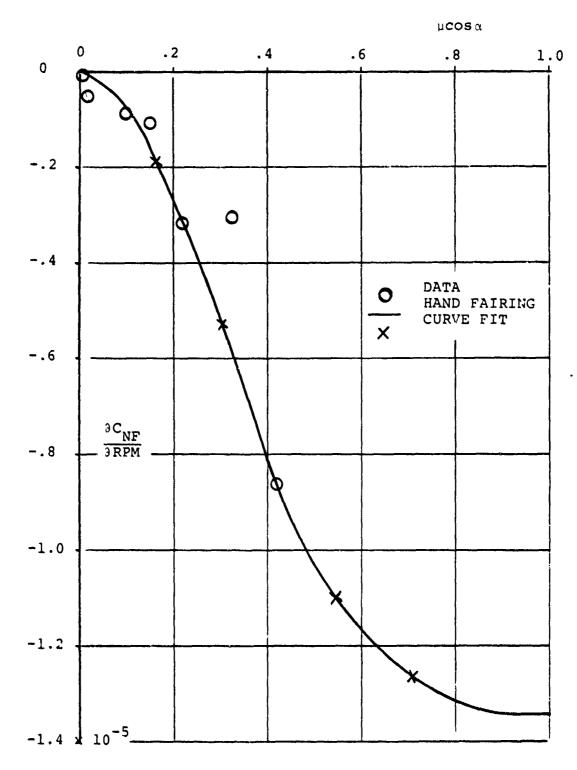


Figure 3-11. Variation of $\frac{3C_{NF}}{3A_{1}}$ with $\mu\cos\alpha$.









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Figure 3.15. Variation of $\partial C_{NF}/\partial RPM$ with $\mu\cos\alpha$.

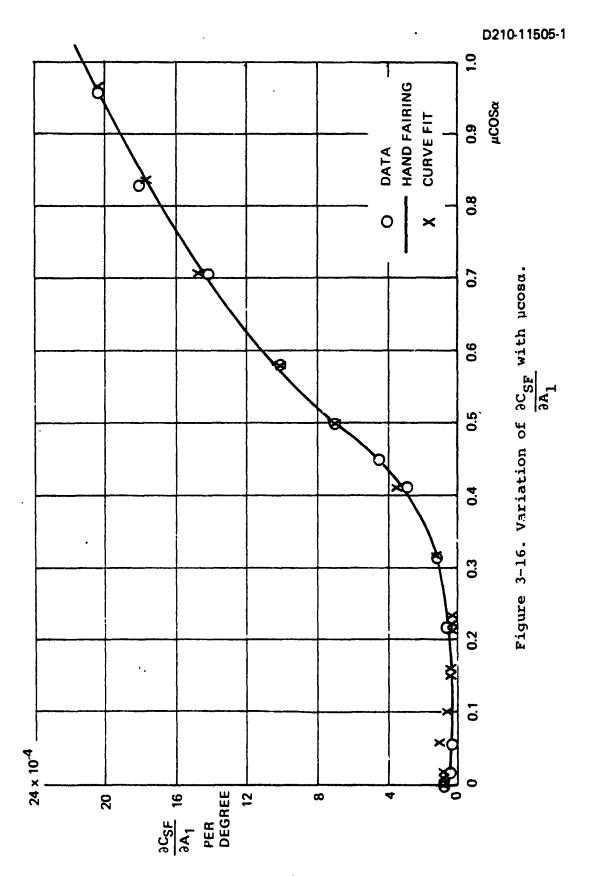
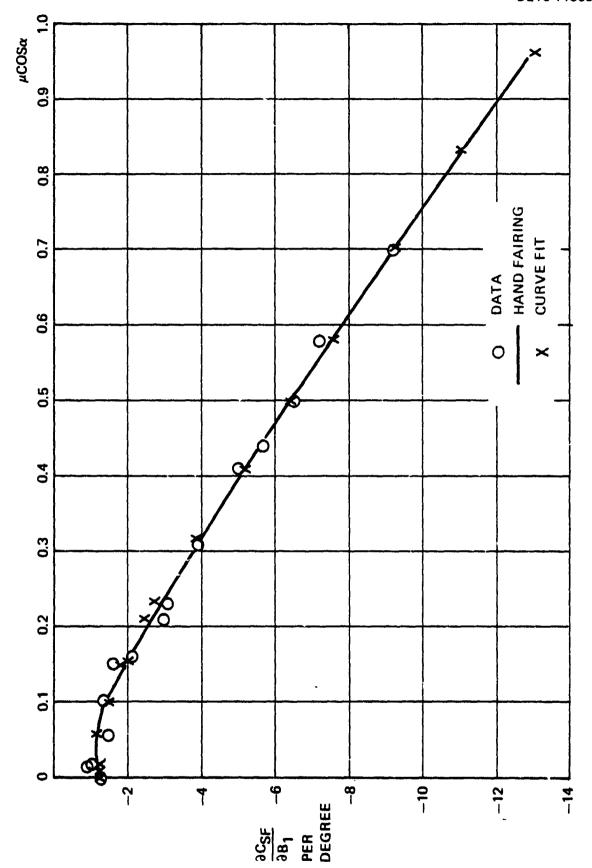


Figure 3-17. Variation of $\frac{\partial C_{\mathrm{SF}}}{\partial B_{1}}$ with $\mu \cos \alpha$.



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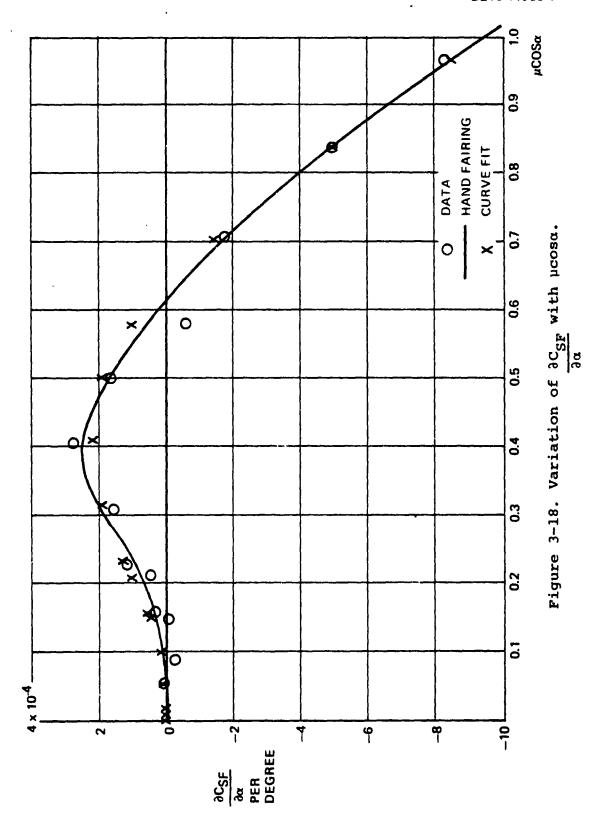
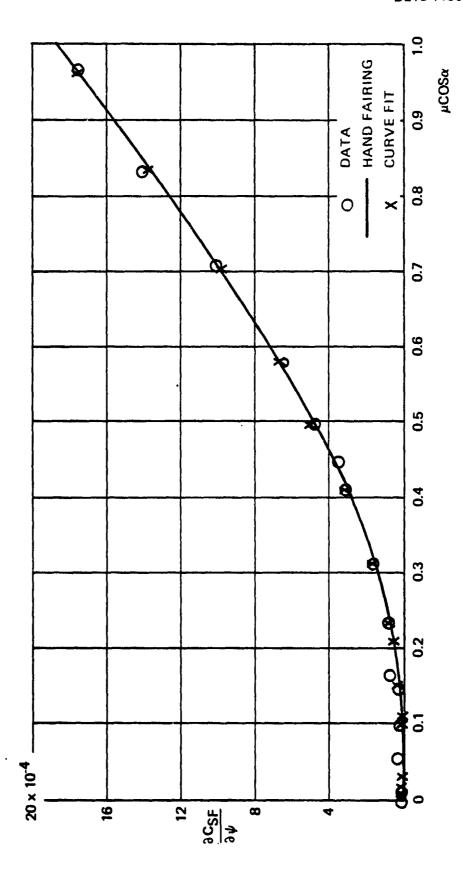


Figure 3-19. Variation of ${}^{\partial C}_{\underline{SF}}$ with $\mu cos\alpha.$



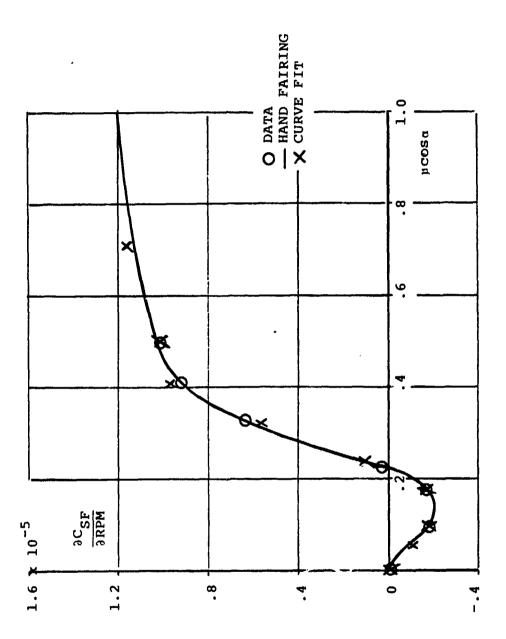


Figure 3.20. Variation of $\partial C_{\text{SP}}/\partial RPM$ with $\mu\cos\alpha$.

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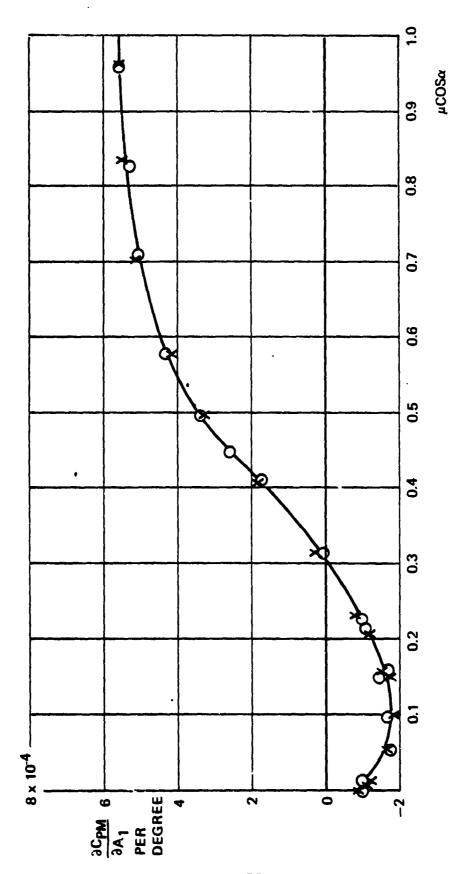


Figure 3-21. Variation of $\frac{3C_{\rm PM}}{3A_{\rm L}}$ with $\mu\cos\alpha$.

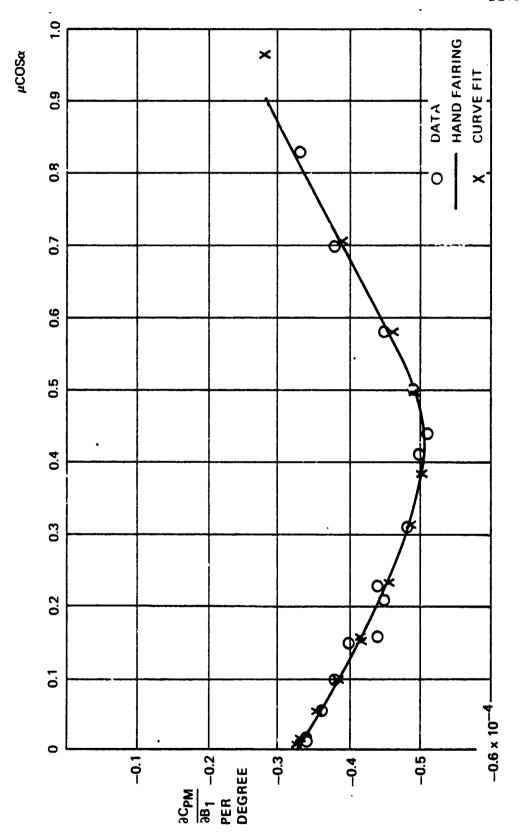
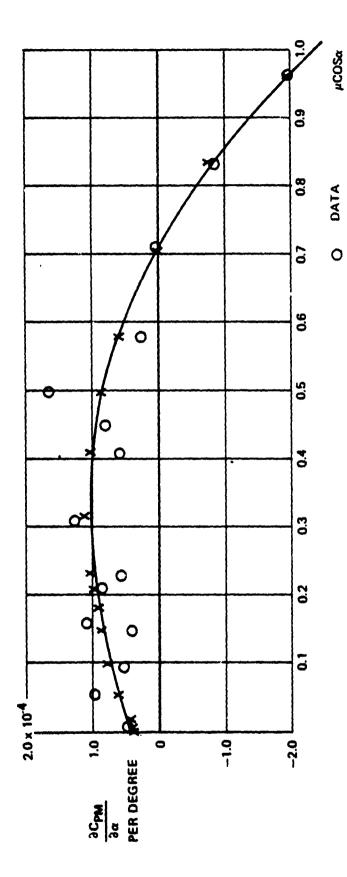


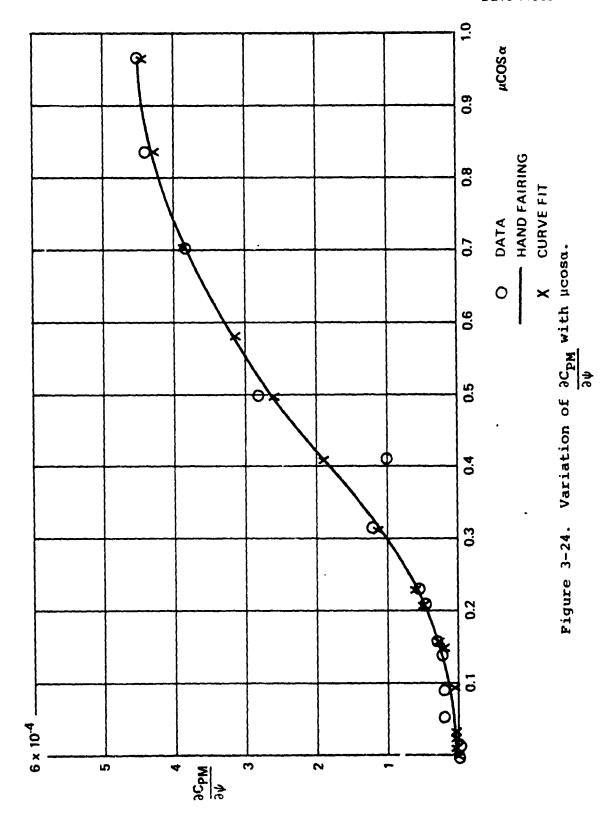
Figure 3-22. Variation of $\frac{\partial C_{PM}}{\partial B_1}$ with $\mu \cos \alpha$.

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Figure 3-23. Variation of $\frac{\partial C_{PM}}{\partial \alpha}$ with $\mu\cos\alpha$.



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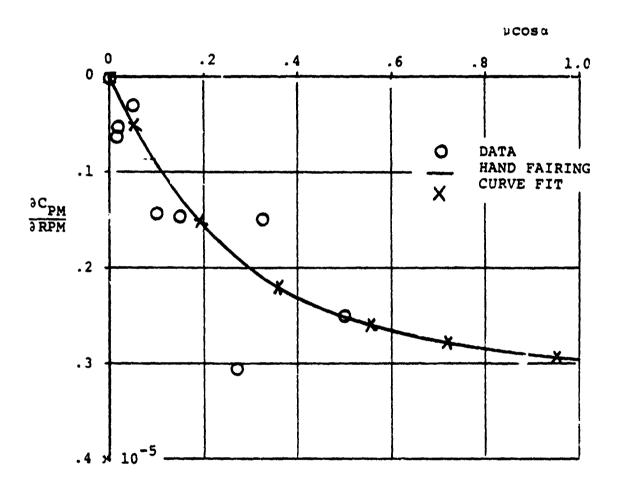
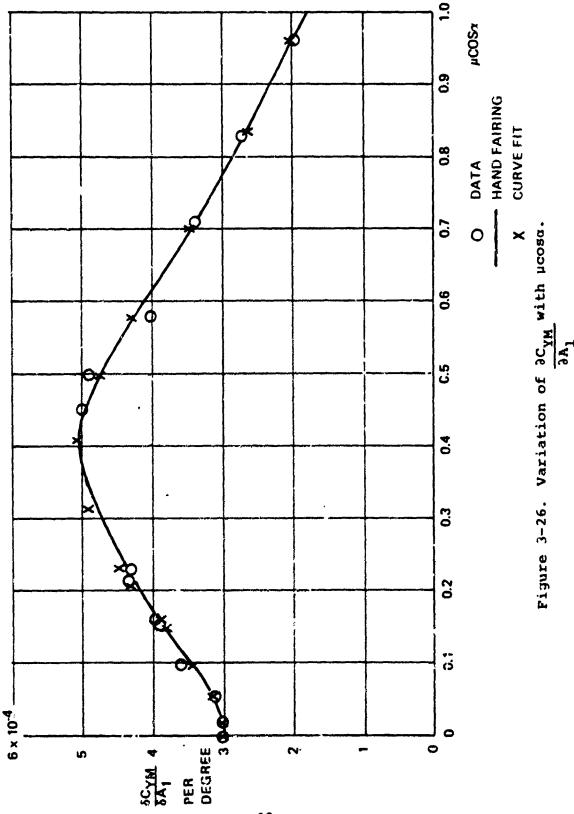
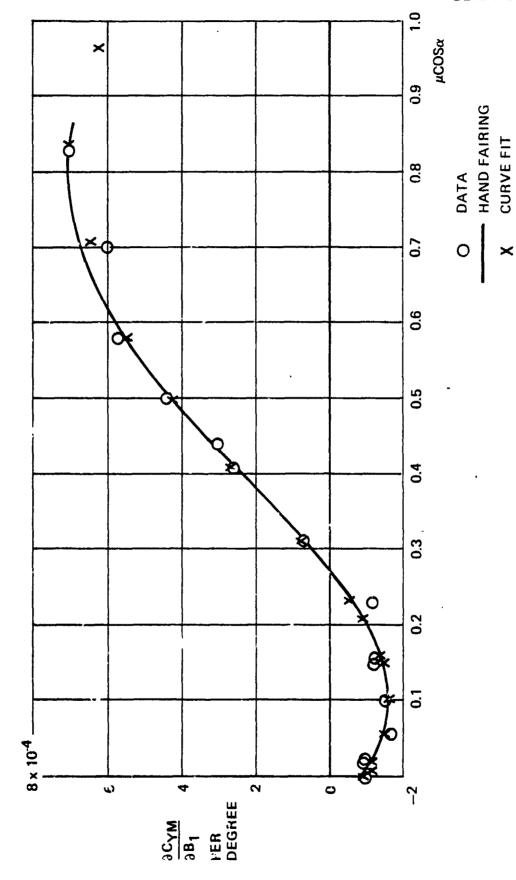


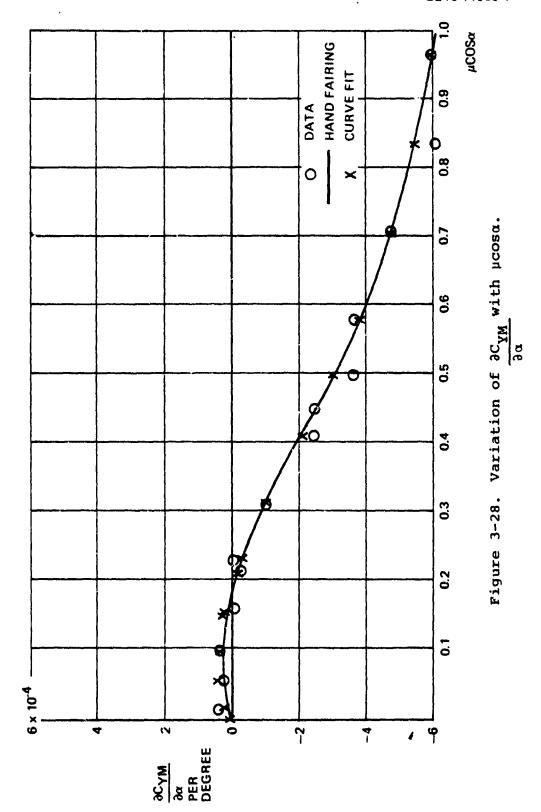
Figure 3.25. Variation of $\partial C_{pM}/\partial RPM$ with $\mu \cos \alpha$.

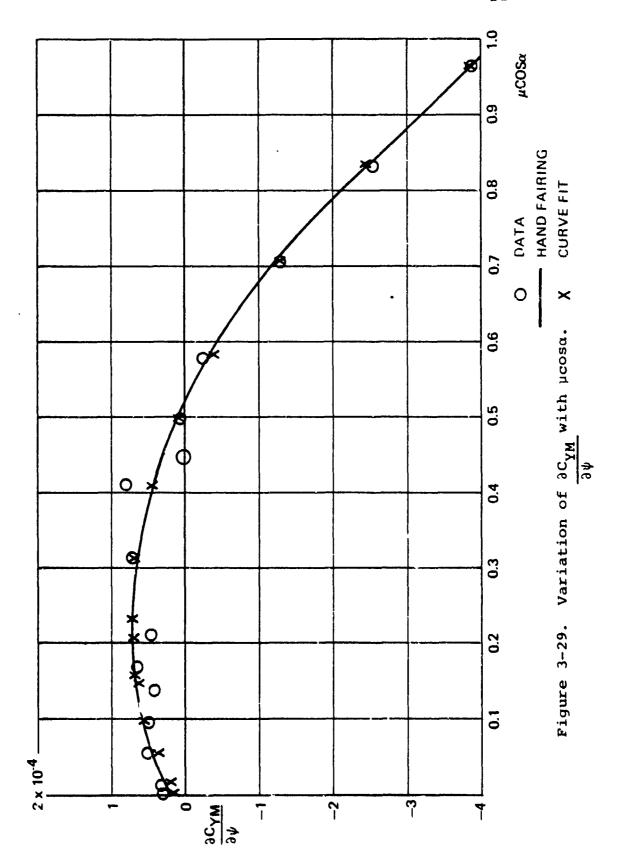


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Figure 3-27. Variation of $\frac{\partial C_{YM}}{\partial B_1}$ with $\mu \cos \alpha$.







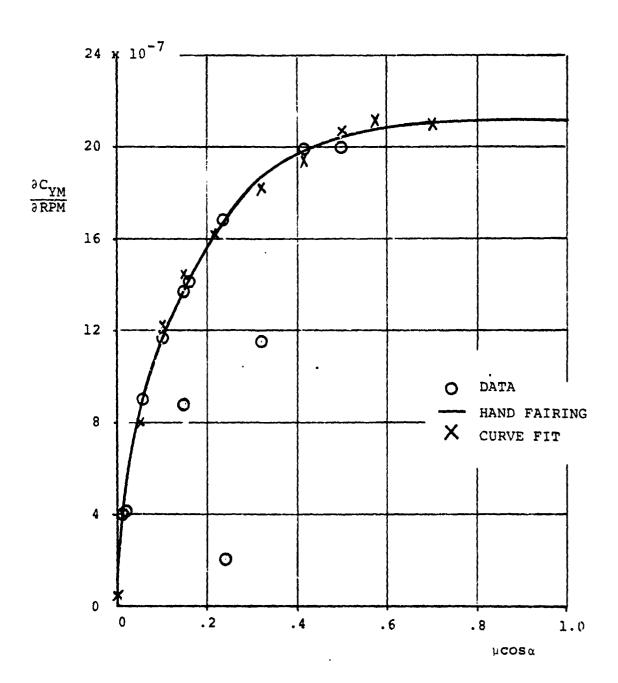


Figure 3.30. Varation of $\partial C_{\mbox{YM}}/\partial RPM$ with $\mu \cos \alpha$.

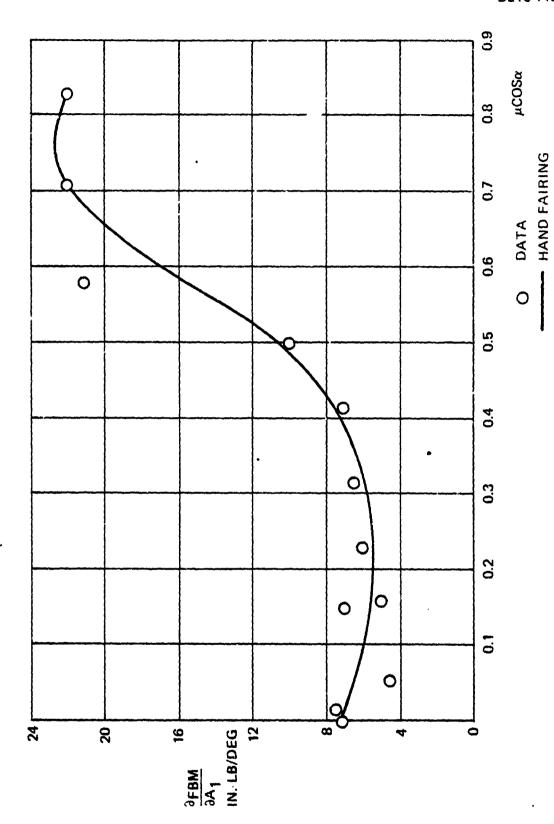
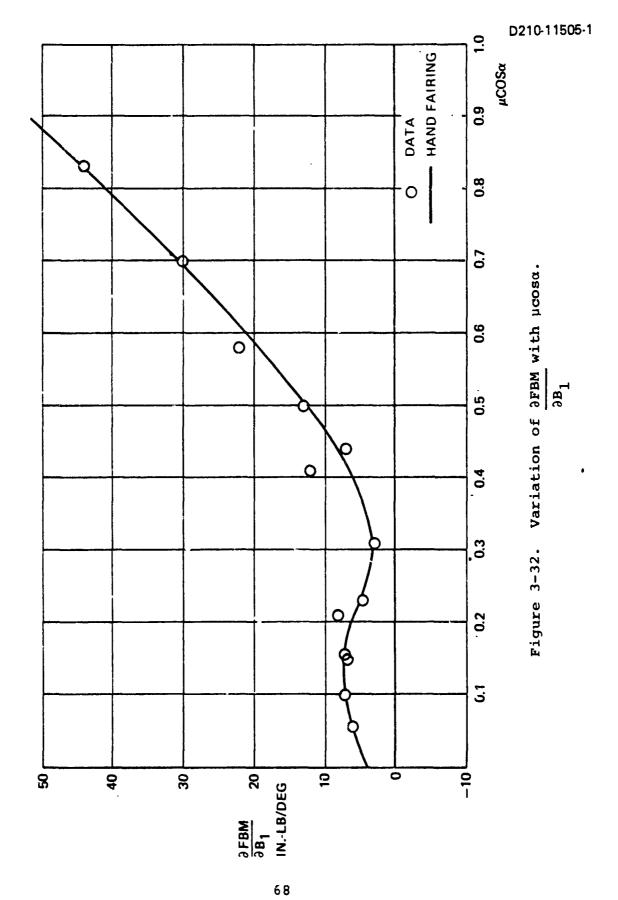


Figure 3-31. Variation of $\frac{3FBM}{3A_1}$ with $\mu\cos\alpha$.



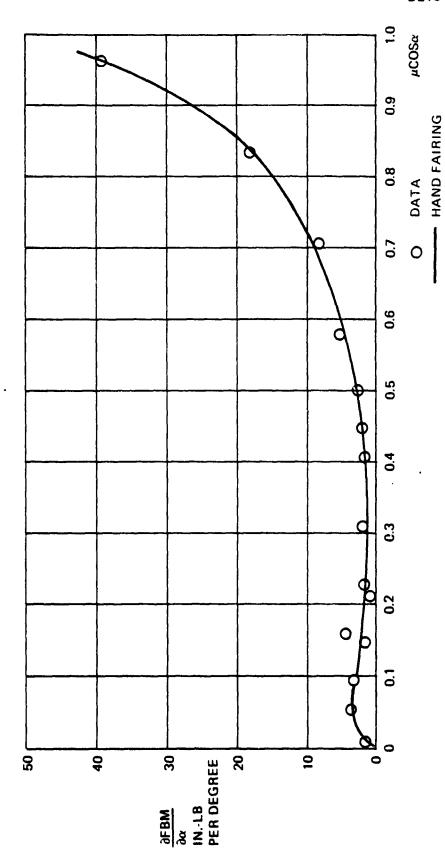
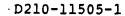


Figure 3-33. Variation of $\frac{\partial FBM}{\partial \alpha}$ with $\mu \cos \alpha$.



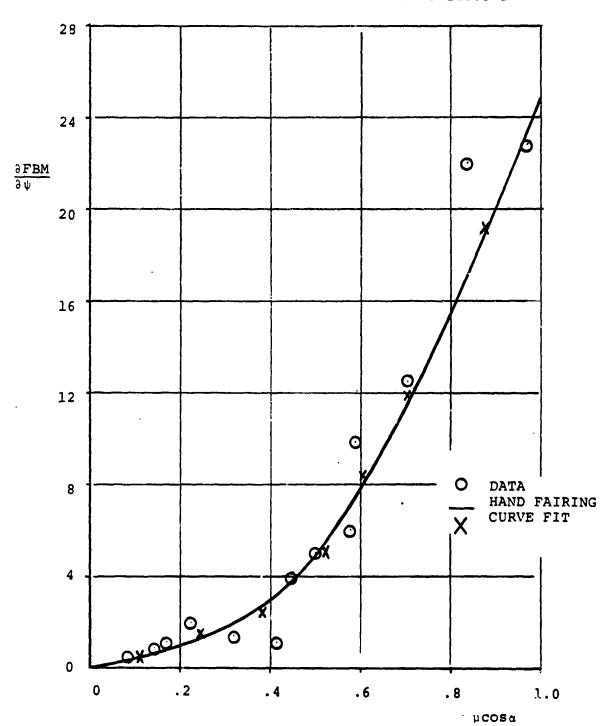


Figure 3.34. Variation of $\partial FBM/\partial \psi$ with $\mu \cos \alpha$.

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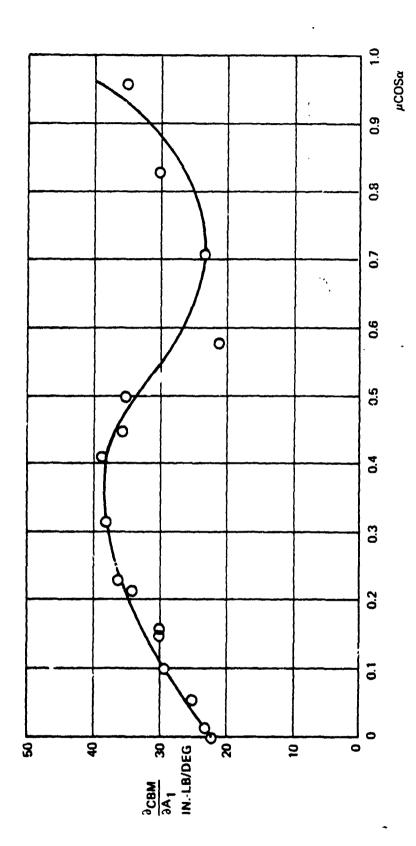


Figure 3-35. Variation of $\frac{\partial CBM}{\partial A_1}$ with $\mu \cos \alpha$.

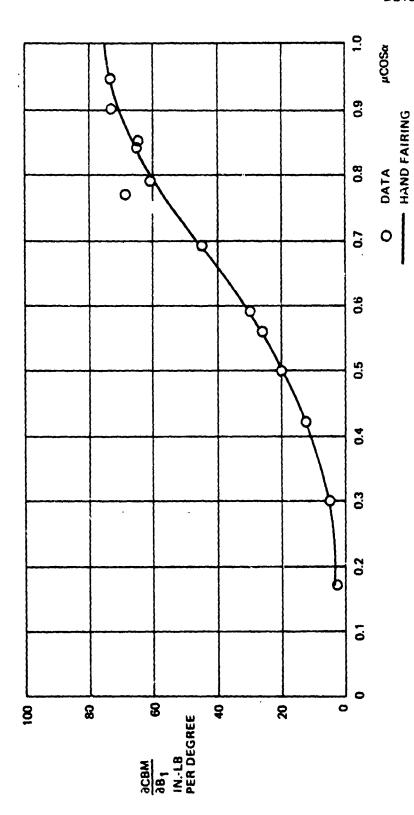
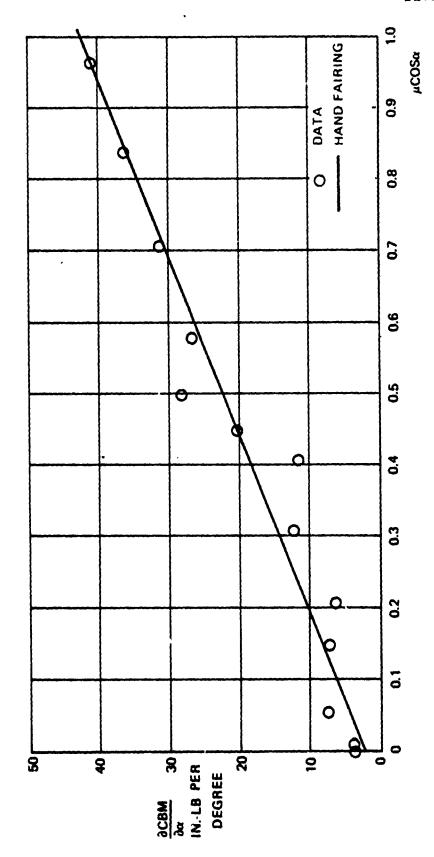


Figure 3-36. Variation of $\frac{3CBM}{3B_{1}}$ with $\mu\cos\alpha$.

Figure 3-37. Variation of $\frac{\partial CBM}{\partial \alpha}$ with $\mu \cos \alpha$.



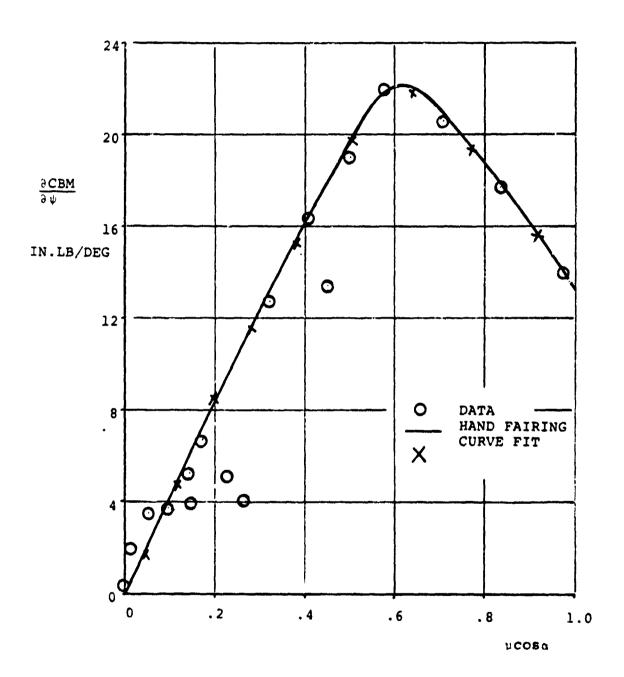
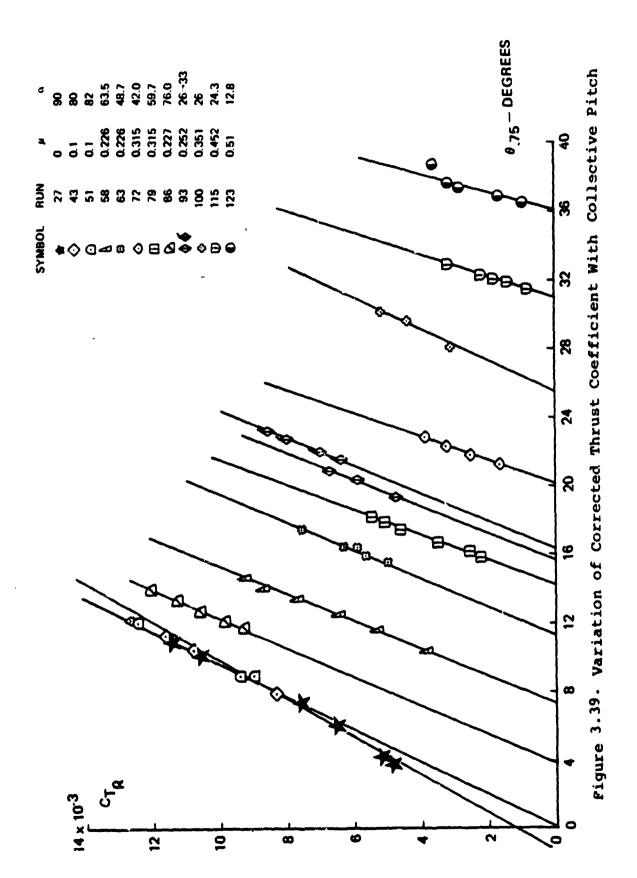


Figure 3.38. Variation of $\partial CBM/\partial \psi$ with $\mu \cos \alpha$.

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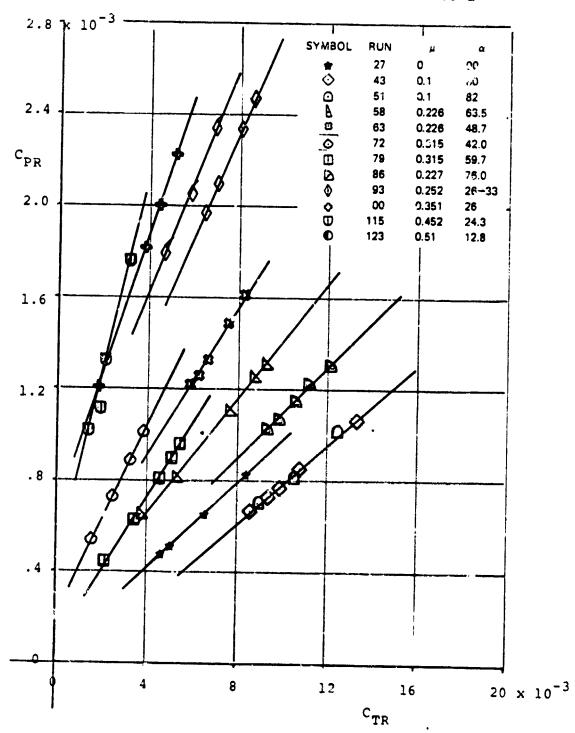


Figure 3.40. Corrected Power Coefficient versus Corrected Thrust Coefficient

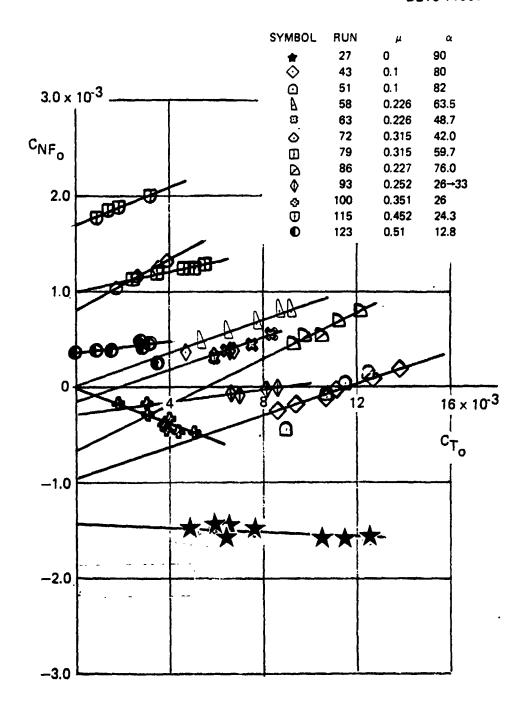


Figure 3.41. Corrected Normal Force Coefficient Versus Corrected Thrust Coefficient

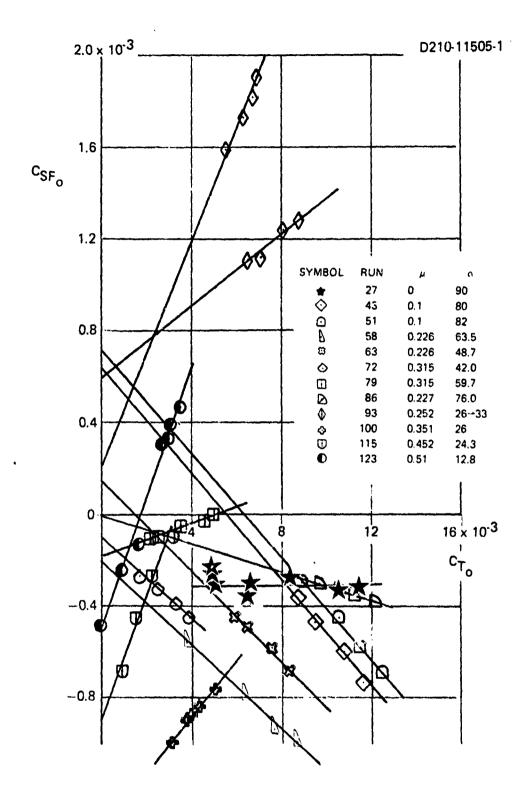


Figure 3.42. Corrected Sideforce Coefficient Versus Corrected Thrust Coefficient



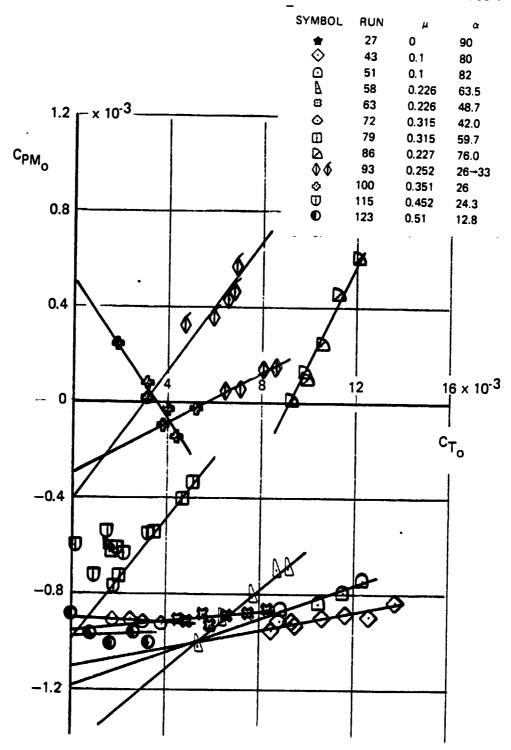


Figure 3.43. Corrected Pitching Moment Coefficient Versus Corrected Thrust Coefficient



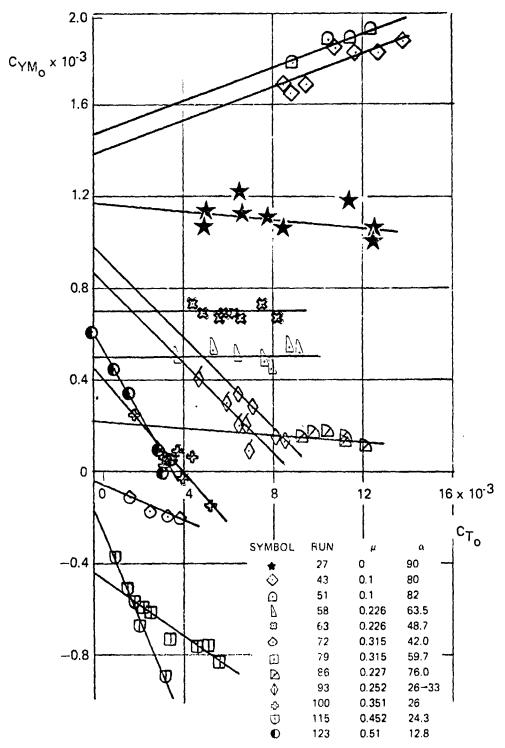


Figure 3.44. Corrected Yawing Moment Coefficient Versus Corrected Thrust Coefficient



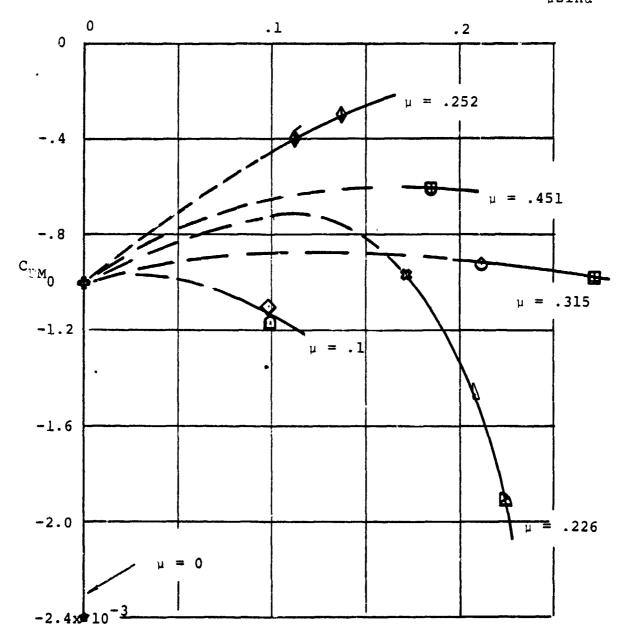


Figure 3.45. Variations of the Reduced Pitching Moment Coefficient at Zero Thrust with $\mu \sin \alpha$

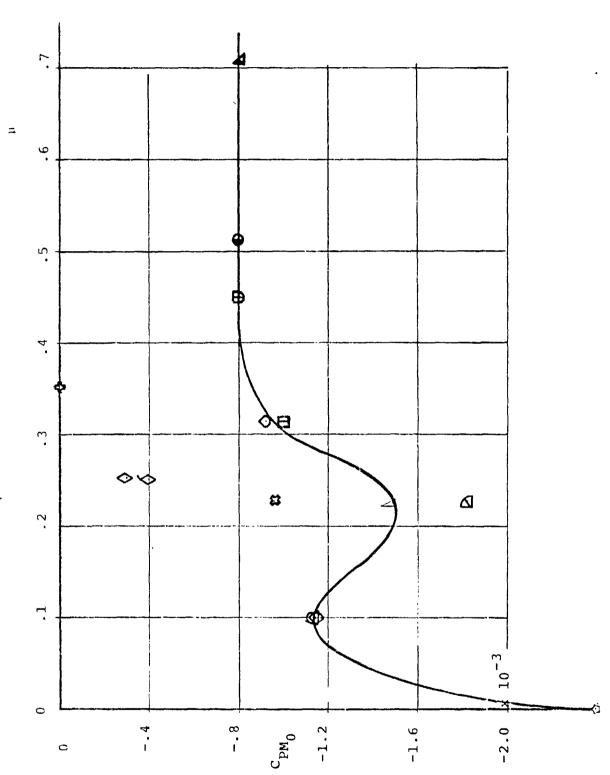
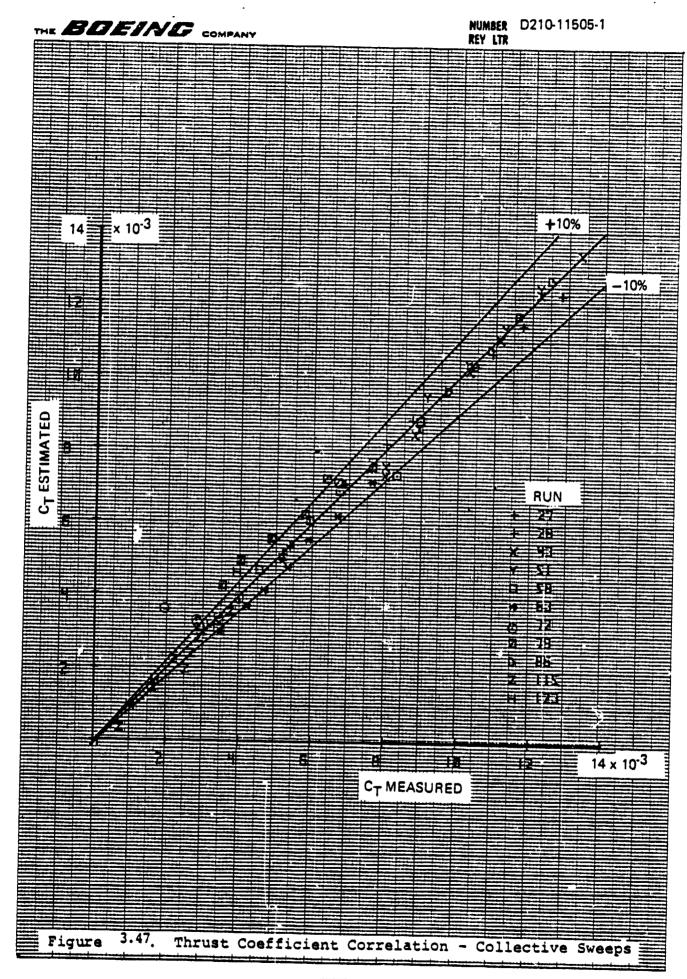
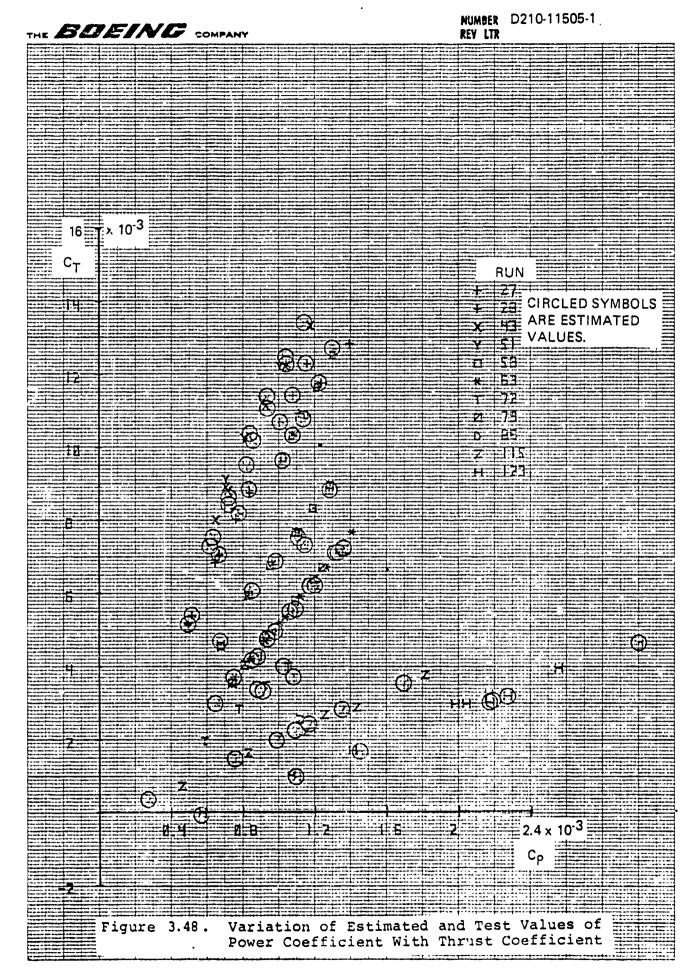
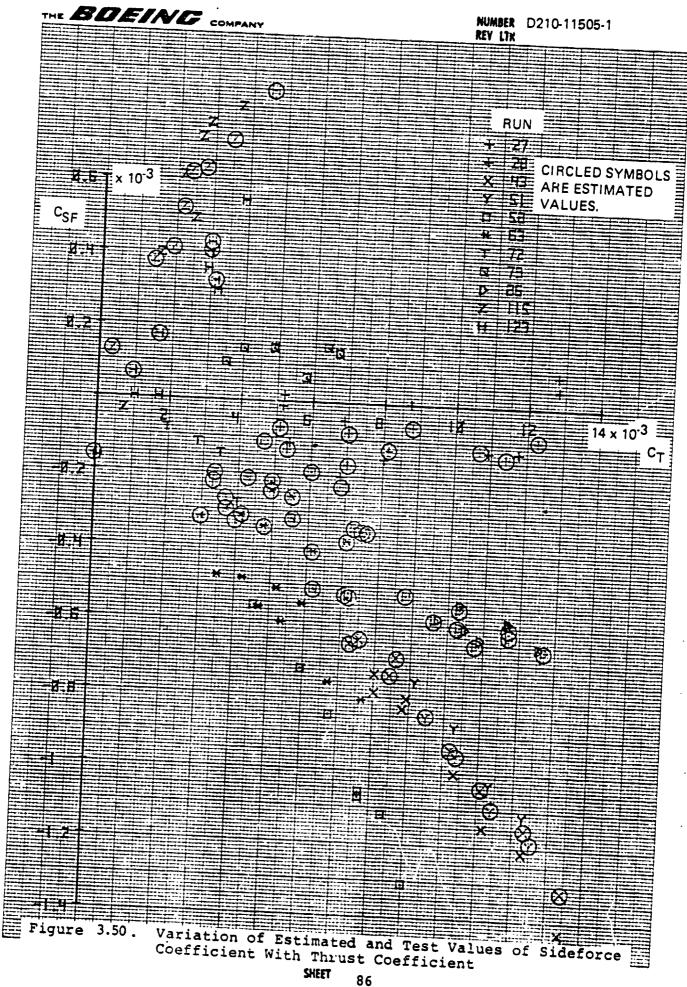


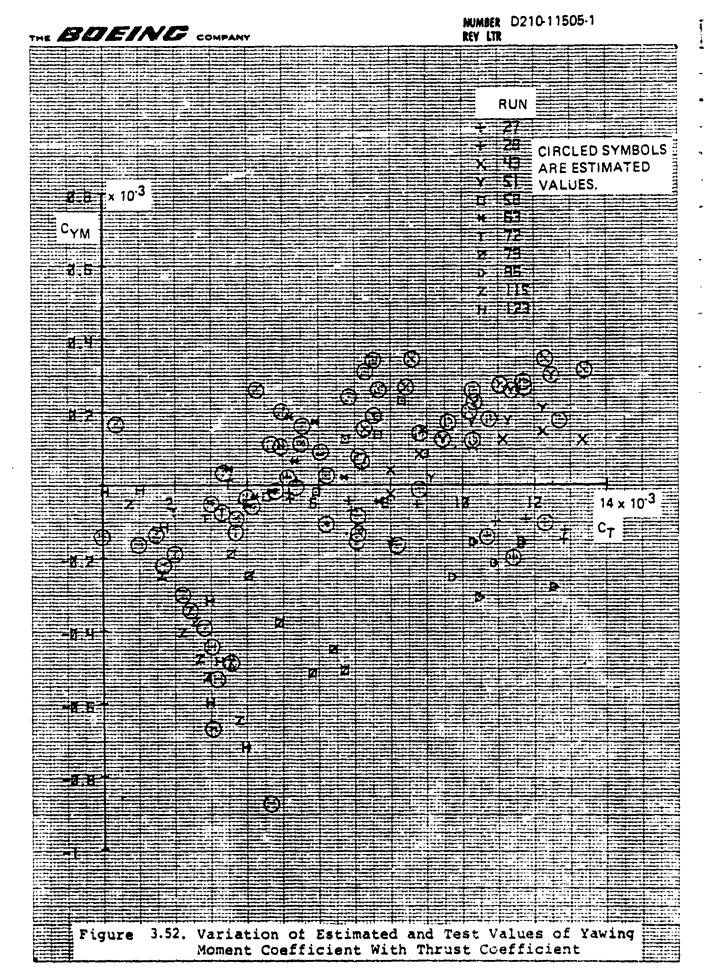
Figure 3.46. Illustration of Method of Fitting the Reduced Data.





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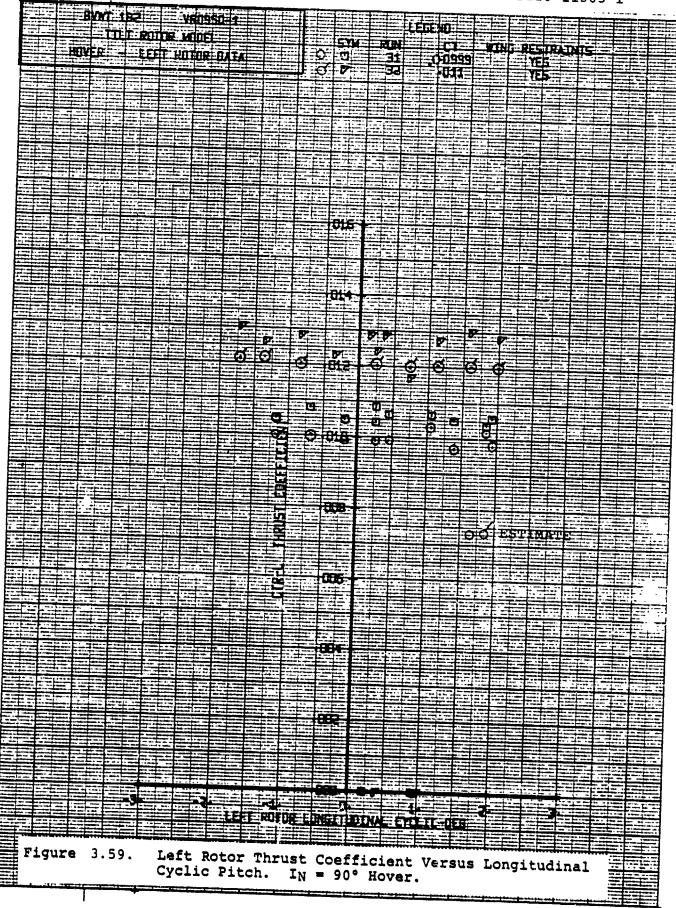
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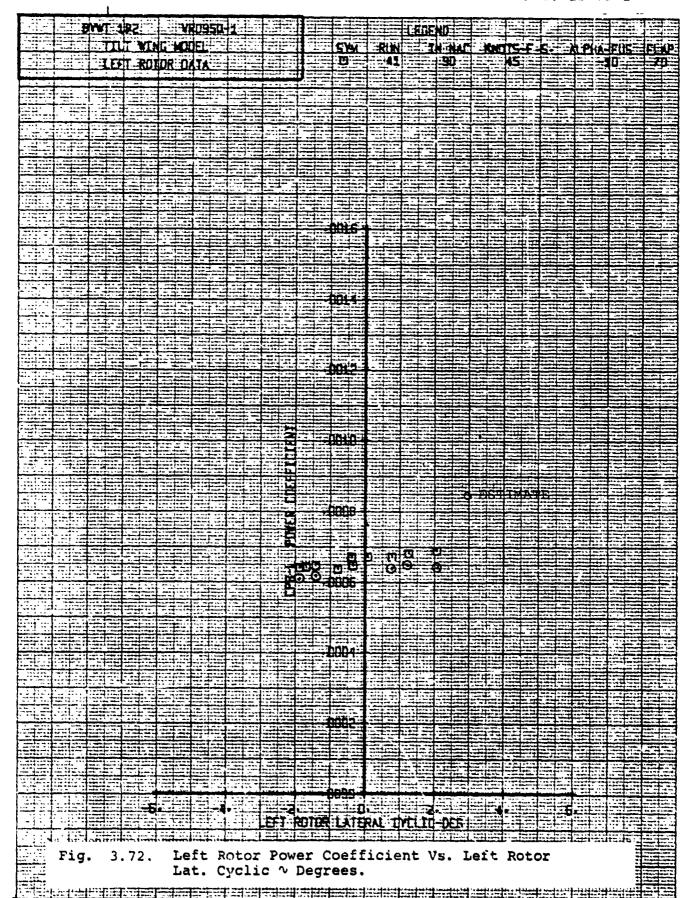
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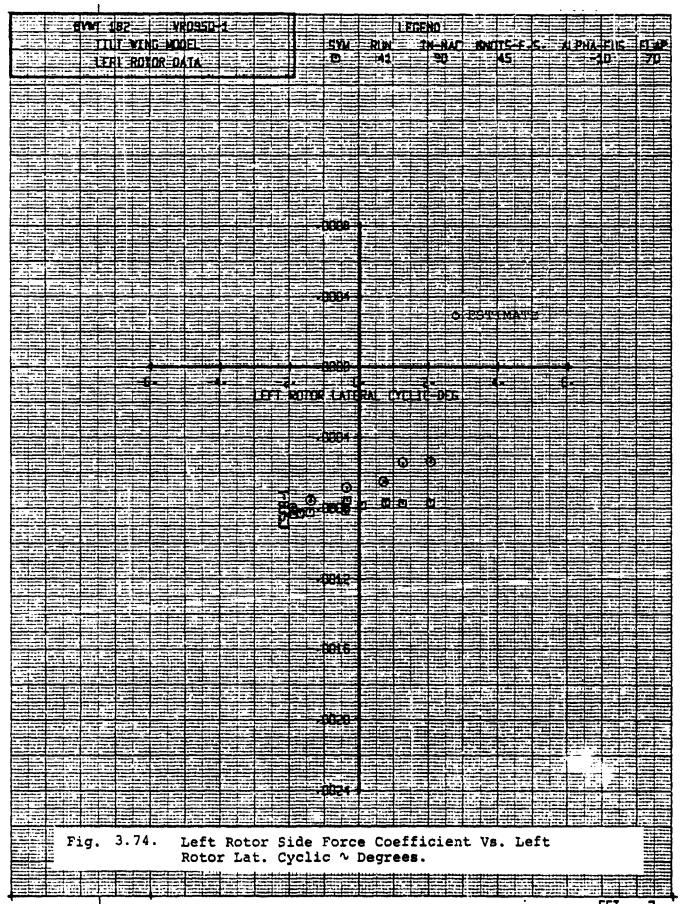
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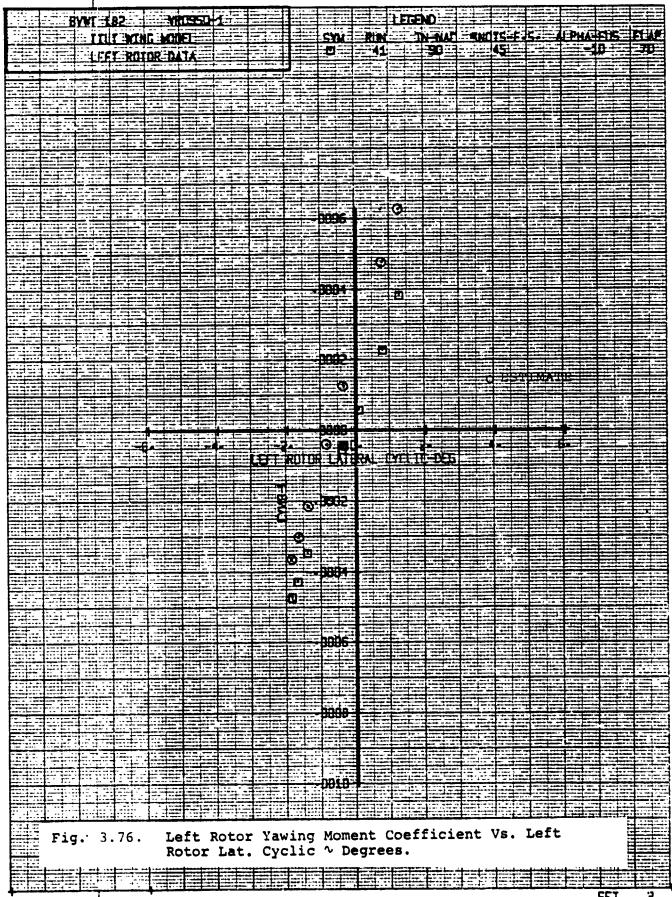
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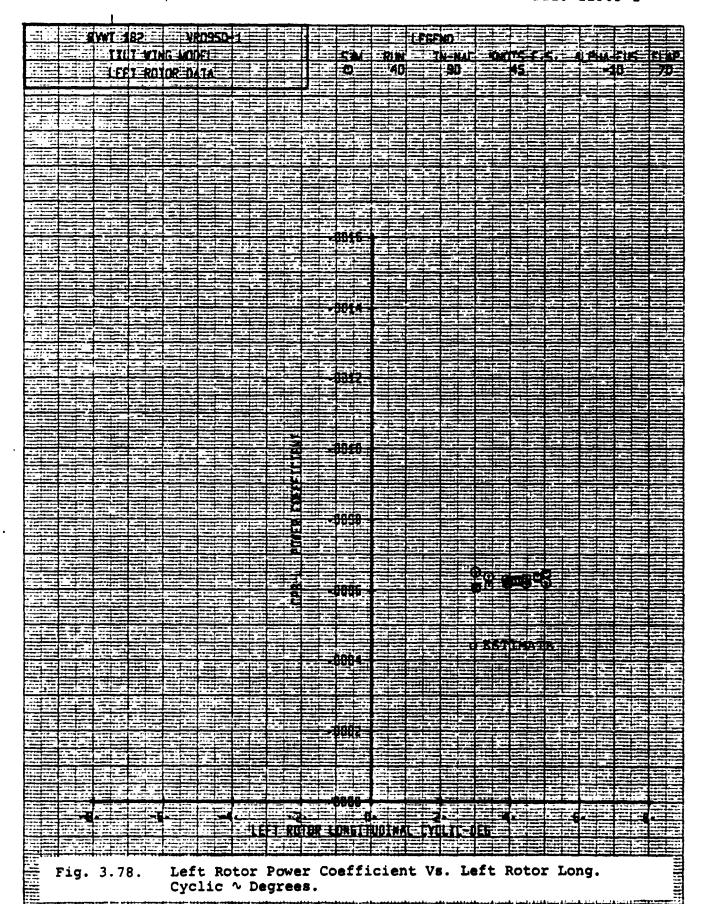
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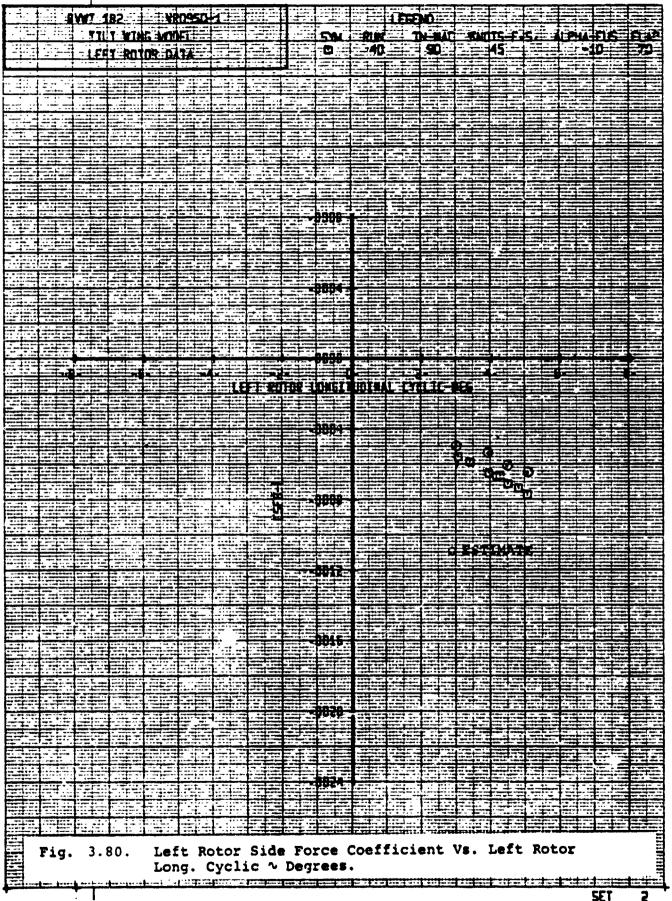
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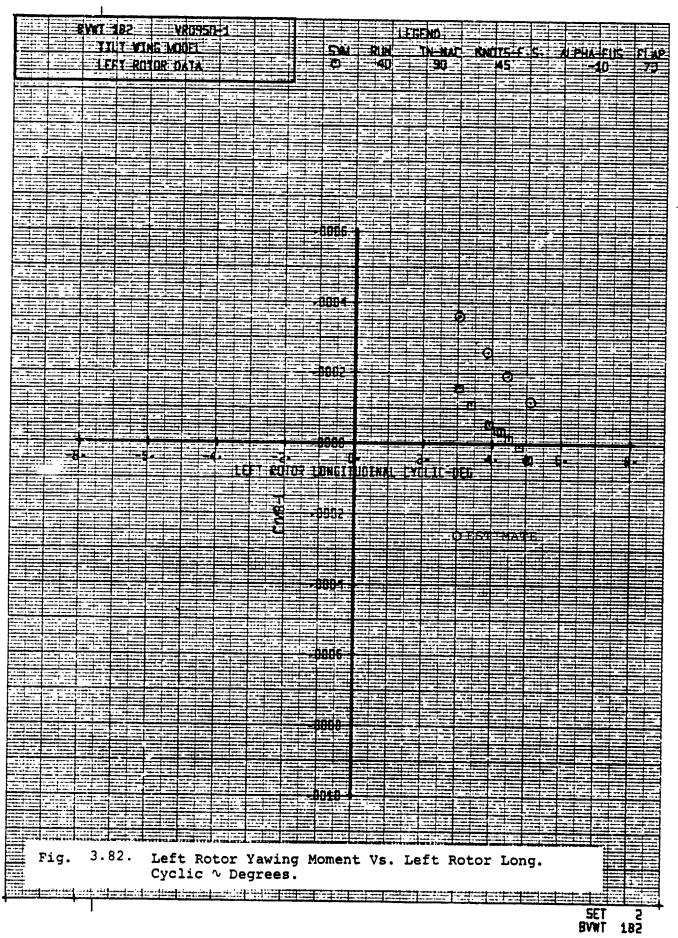
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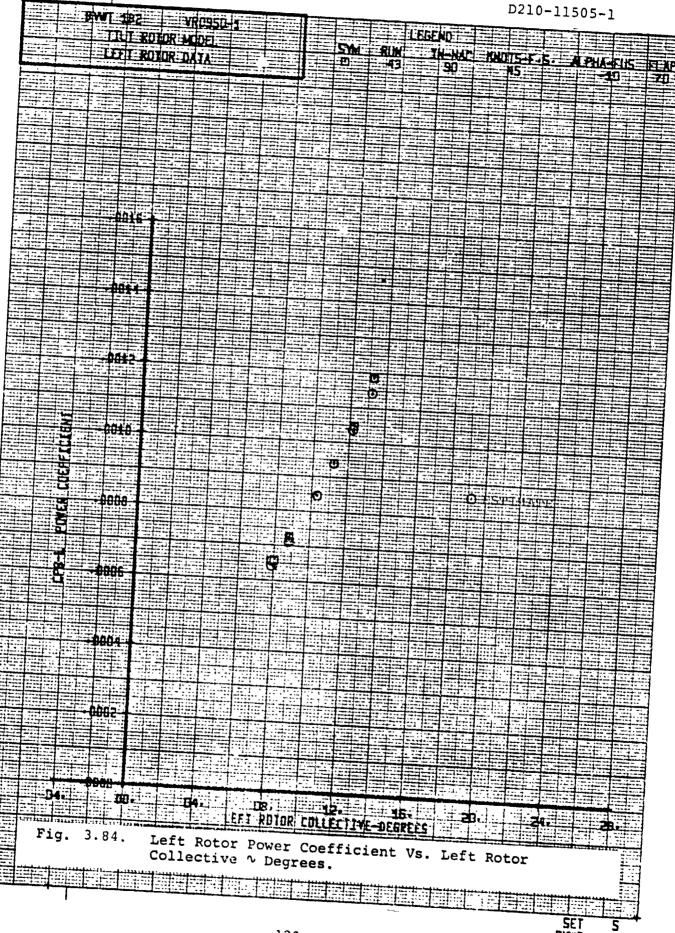
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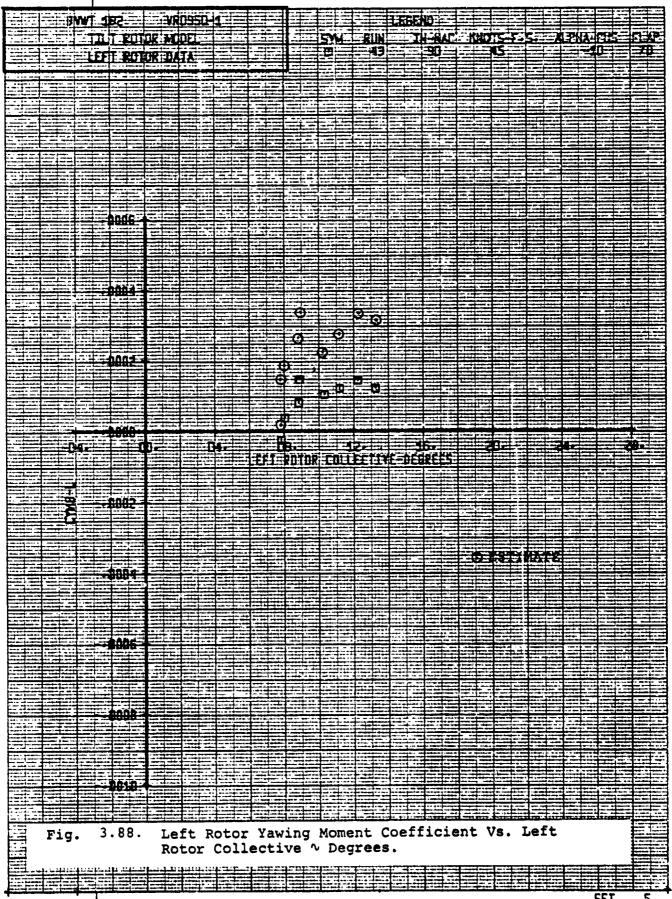
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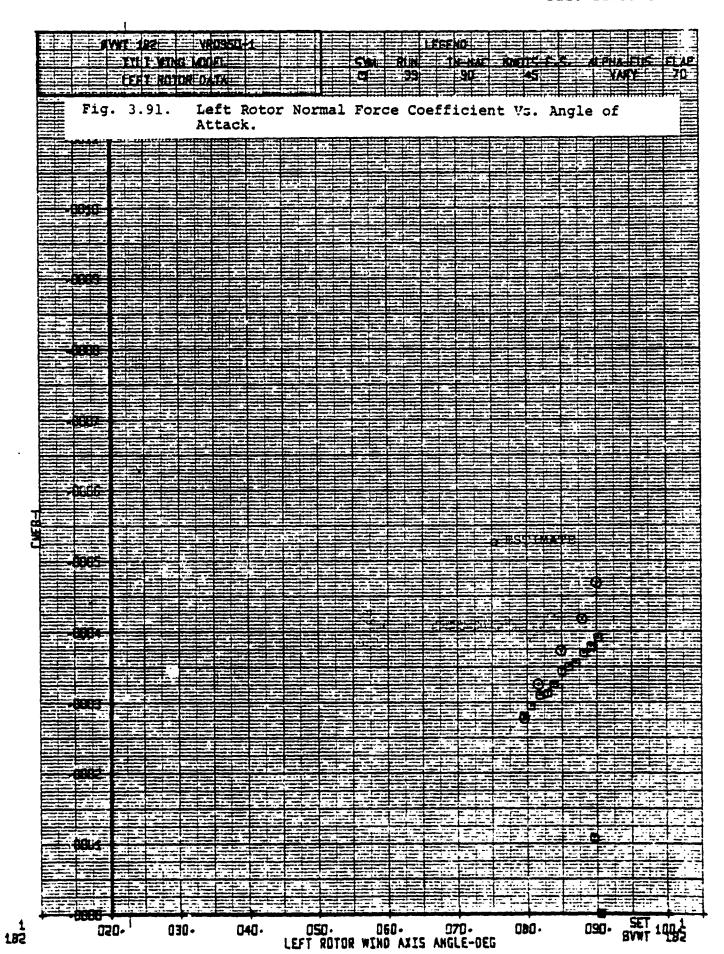


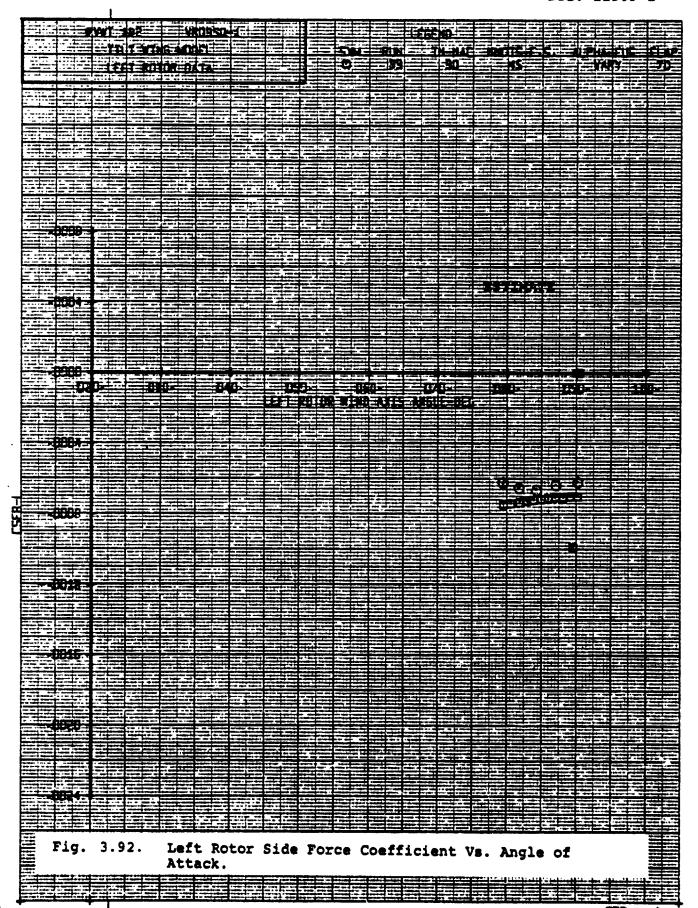
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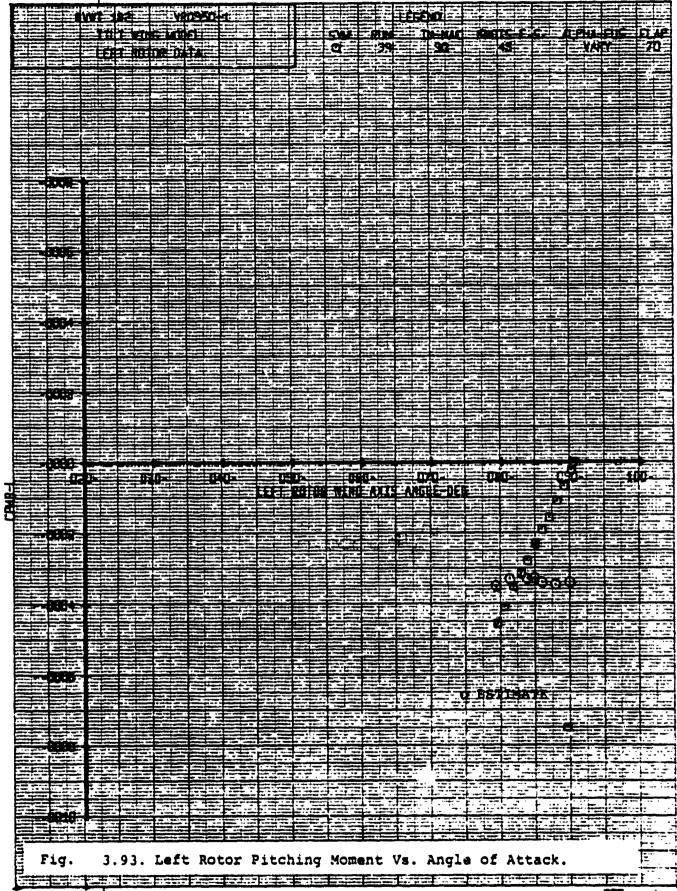
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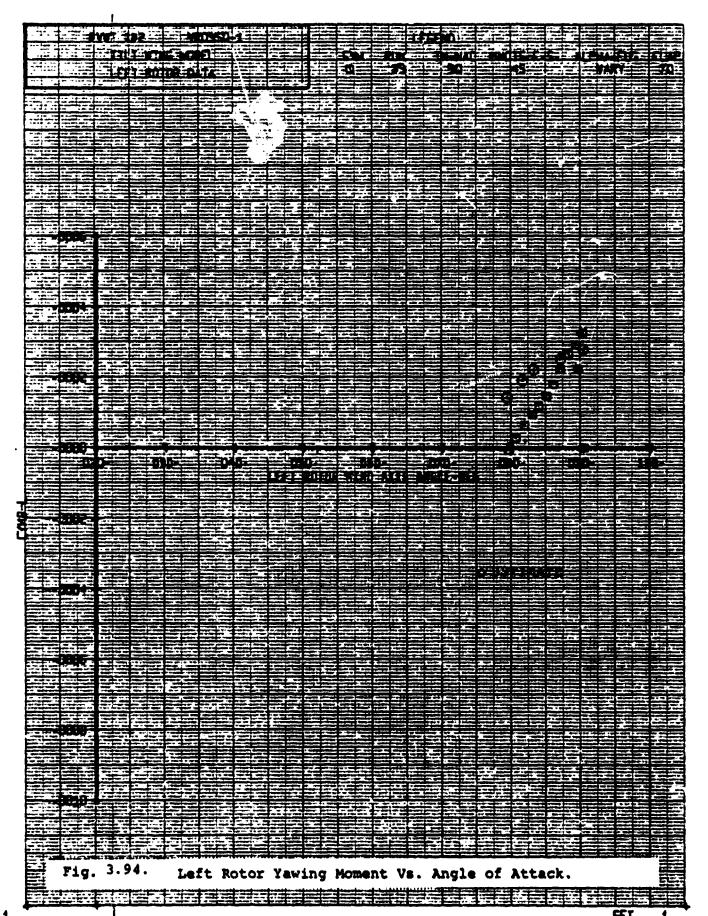


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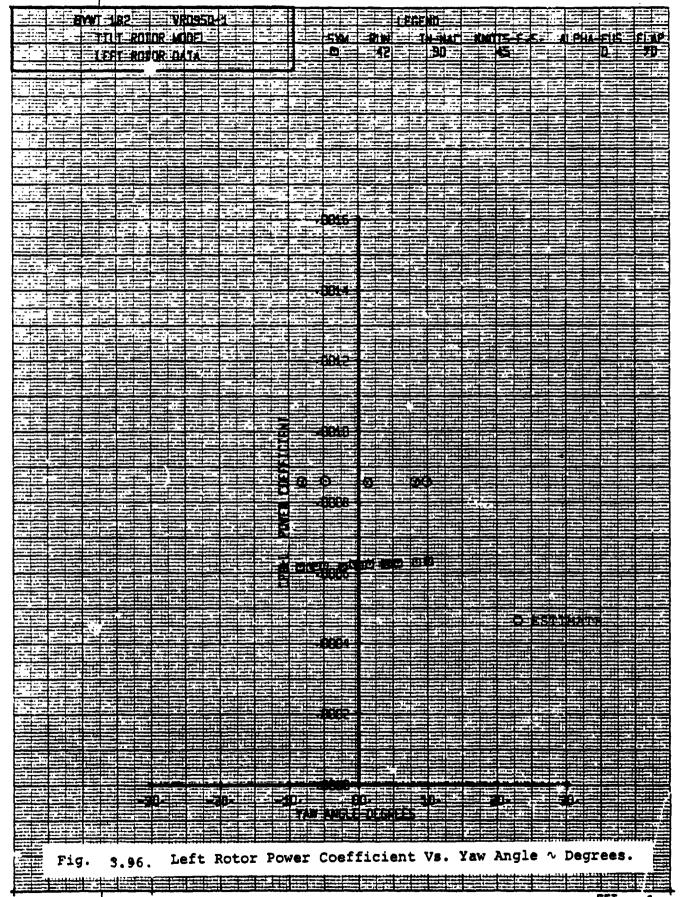
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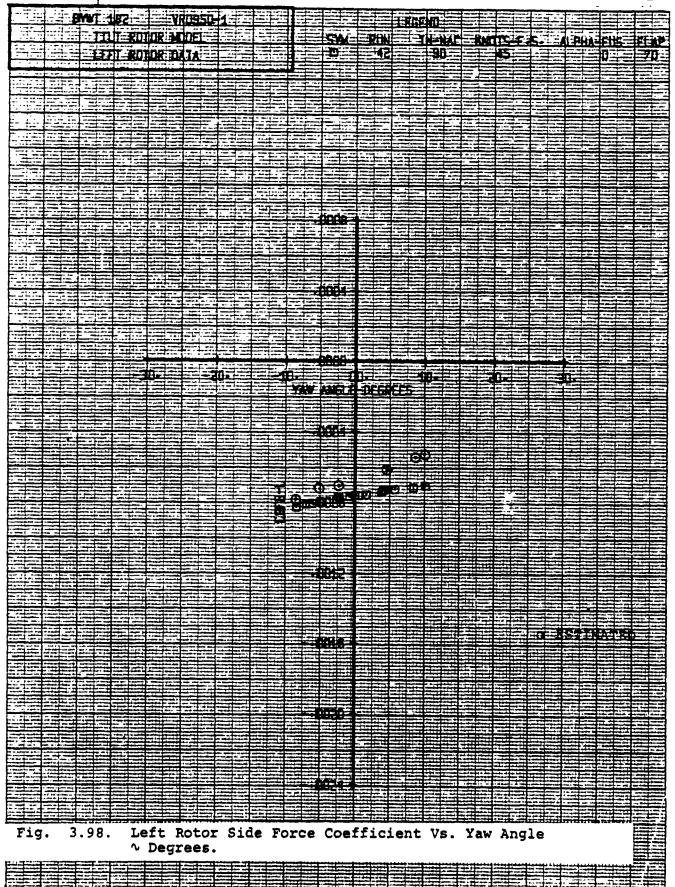


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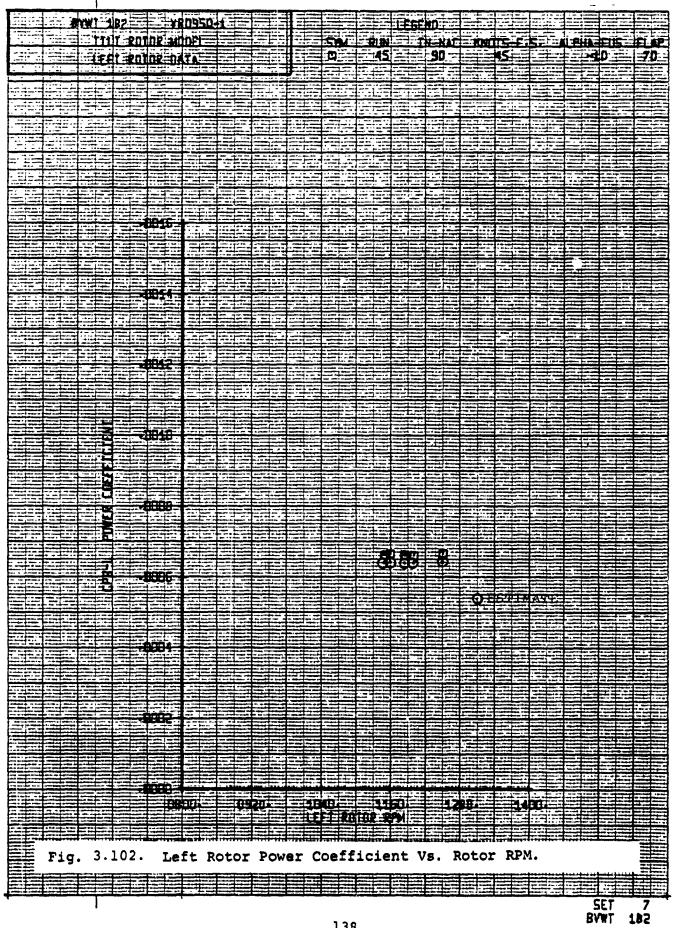
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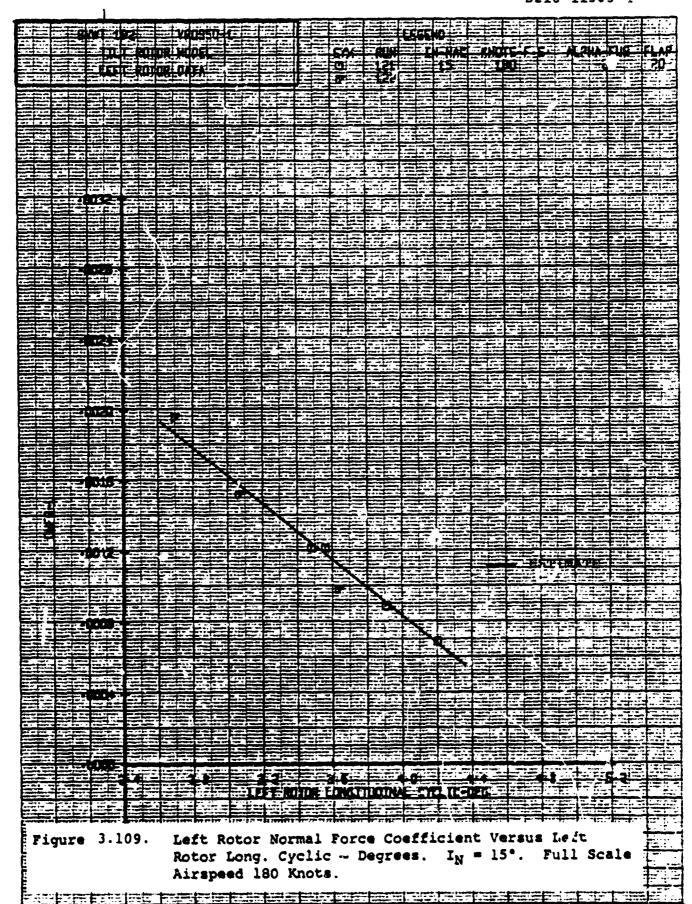
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얼룩될라#중취르면행해!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
Figure 3.107. Left Rotor Thrust Coefficient Versus Left Rotor
Long. Cyclic ~ Degrees. I _N = 15°. Full Scale
Airspeed 180 Knots.
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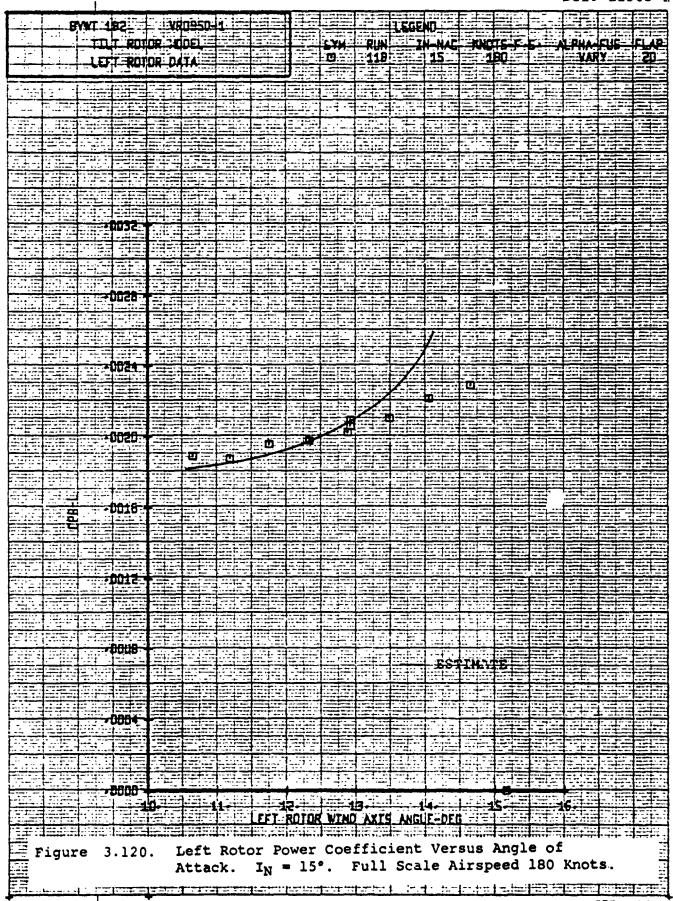
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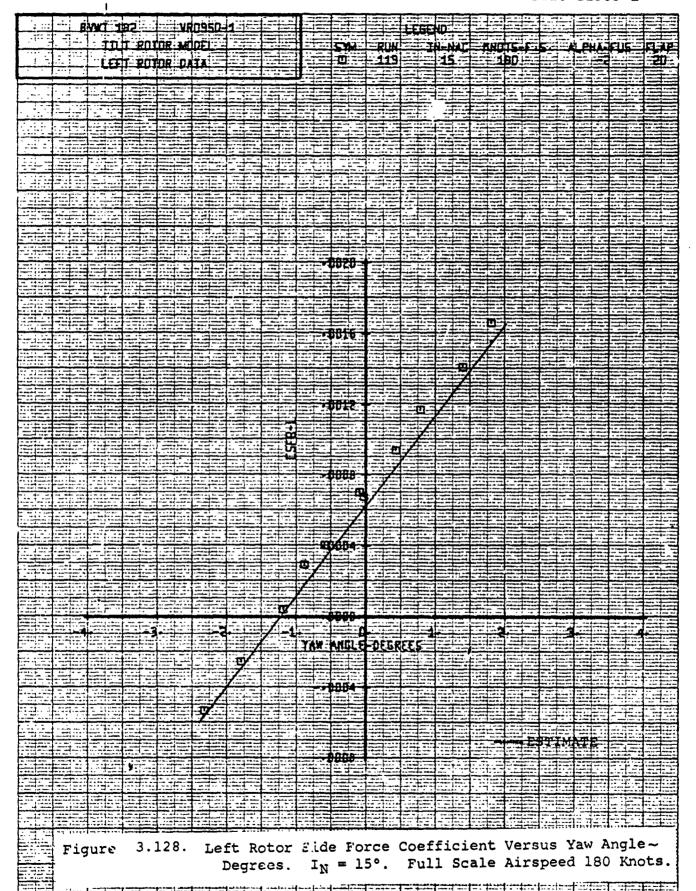
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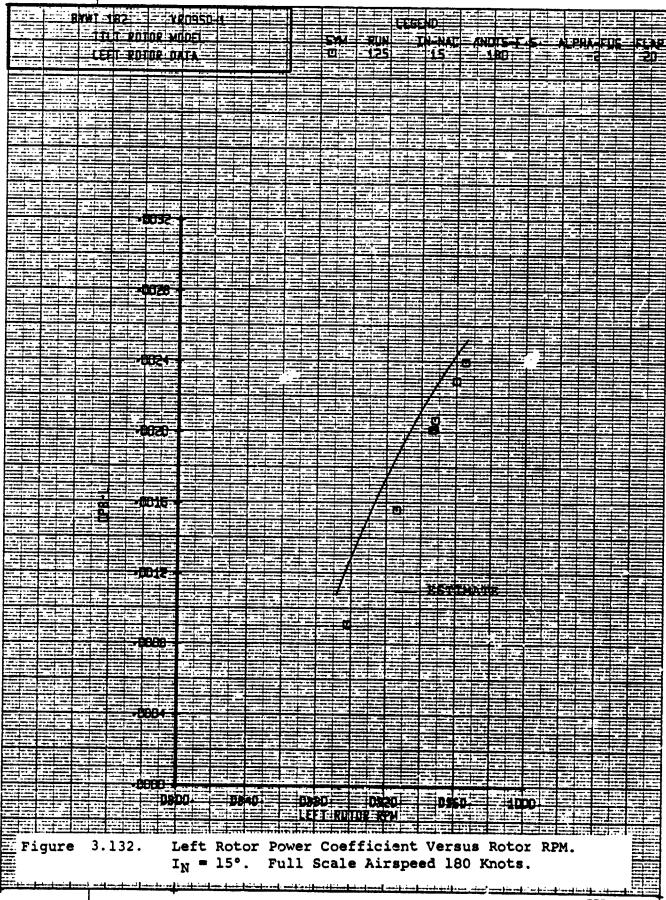
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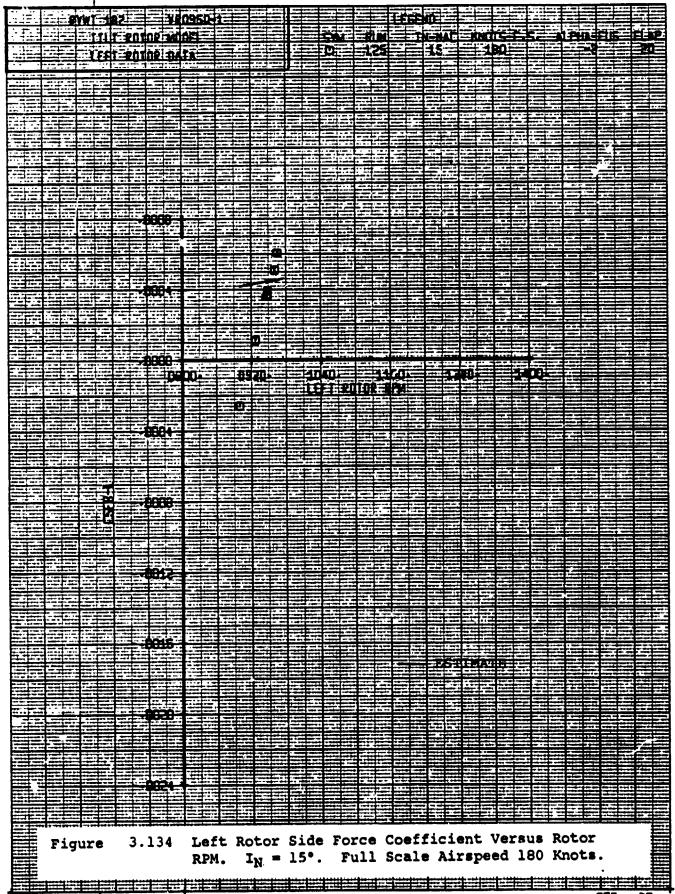
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APPENDIX A. APPLICATION OF LINEAR REGRESSION TECHNIQUES

As mentioned in the Introduction, an attempt was made to apply multivariable linear regression techniques to the data. This was motivated by the need to process the large amount of data available in the shortest time. A brief description of the procedure and the results is given here.

The basis of the approach was that each component of force or moment was functionally of the form

$$C_{F} = C_{F0} (\alpha, \mu, \Omega, \theta_{.75}, A_{1}, B_{1}) + \frac{\partial C_{F}}{\partial A_{1}} A_{1} + \frac{\partial C_{F}}{\partial B_{1}} B_{1}$$
where
$$\frac{\partial C_{F}}{\partial A_{1}} \frac{\partial C_{F}}{\partial B_{1}} \text{ were, in turn, functions of the}$$

independent variables, i.e.,

$$\frac{\partial C_F}{\partial A_1} = (\alpha, \mu, \Omega, \partial_{.75}, A_1, B_1) \qquad (A-2)$$

Thus each component was to be represented as the sum of the force or moment at zero cyclic, and perturbations in that force produced by the application of the cyclic controls. In principle it appeared possible to read all the wind tunnel data into a data file, specify likely parameters for correlation (for example, $\mu\cos\alpha$, μC_T) and use the linear regression option of a statistical package (STATPAK) to determine how well a linear combination of the selected parameters fitted the data.

The first step in this process was obviously to use the linear regression feature of STATPAK to find the values of the cyclic derivatives $\partial C_F/\partial A_1$, $\partial C_F/\partial B_1$ since this would be faster than calculating the slopes from the wind tunnel data plots. Accordingly those runs in which μ , α , θ , η_3 , and RPM were fixed and A_1 or B_1 varied, were processed by the statistical package. The equation for a particular force coefficient was therefore

$$C_F = a + b A_1$$

where the slope, b, and the intercept, a, were given by the linear regression. The slopes were then plotted against $\mu\cos\alpha$. An inspection of these plots showed considerable scatter in some areas. The wind tunnel data was reviewed and it was then observed that small but significant changes in the values of cyclic and collective (that were nominally fixed) had occurred in a number of the runs. In view of these deviations it was decided to combine the A_1 and B_1 sweep data and introduce thrust coefficient as a variable in the regression equations. The equation form chosen was

$$CF = CF_0 + CF_1 C_T + CF_2 A_1 + CF_3 B_1 + CF_4 A_1 C_T + CF_5 B_1 C_T$$
(A-3)

Using this form in the regression analysis resulted in extremely good correlation being achieved. Figure A-1 presents a comparison of sideforce coefficient computed using equation (A-3) with the measured sideforce, as produced by variations in A and B cyclic at μ = .1 and α = 80°. Agreement is to within 5% of the measured values. Figure A-2 shows similar agreement measured and computed normal forces at μ = .314 and α = 42°.

Since good correlation was achieved using equation A-3 it was anticipated that those portions of the final rotor math model equations which were to represent changes due to cyclic pitch would be written

$$\frac{\partial C_F}{\partial A_1} = CF_2 + CF_4 CT$$

$$\frac{\partial C_F}{\partial B_1} = CF_3 + CF_5 CT$$

The next step was then to determine how the coefficients CF_2 through CF_5 varied with μ , α , β , θ , 75 and hence obtain general equations for $\theta C_{NF}/\theta A_1$, $\theta C_{NF}/\theta B_1$, etc., covering all flight conditions. It was at this point that difficulties were encountered in finding suitable combinations of parameters that would achieve this. The coefficients could not be represented by a simple function of $\mu\cos\alpha$ as is shown by Figure A-3 which presents the variation of the coefficients in the normal force derivative. Combinations of likely parameters such as using μ sin α , μC_T etc. were tried to no avail and it was therefore concluded that some theoretical guidance was required. Thus led to the development of the analysis described in Appendix B.

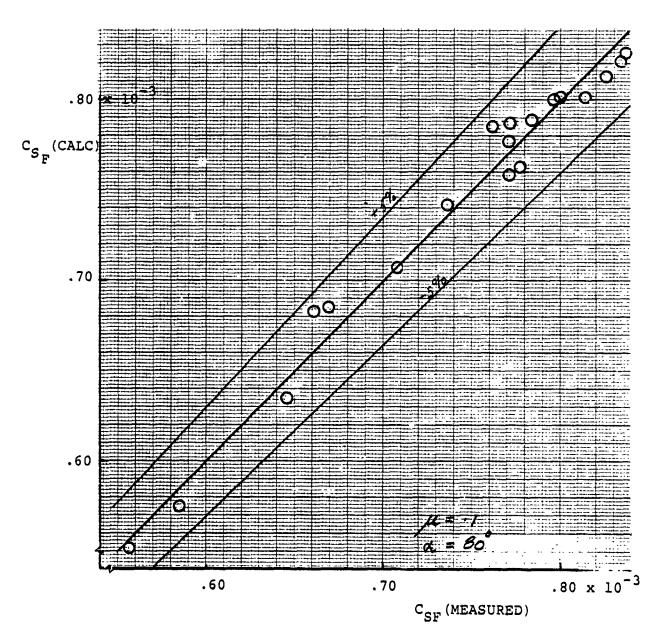


FIGURE A-1. COMPARISON OF MEASURED AND CALCULATED SIDEFORCE COEFFICIENTS USING THE REGRESSION TECHNIQUE

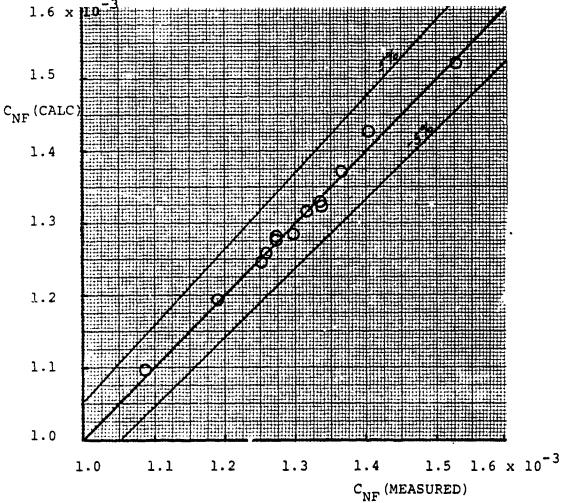
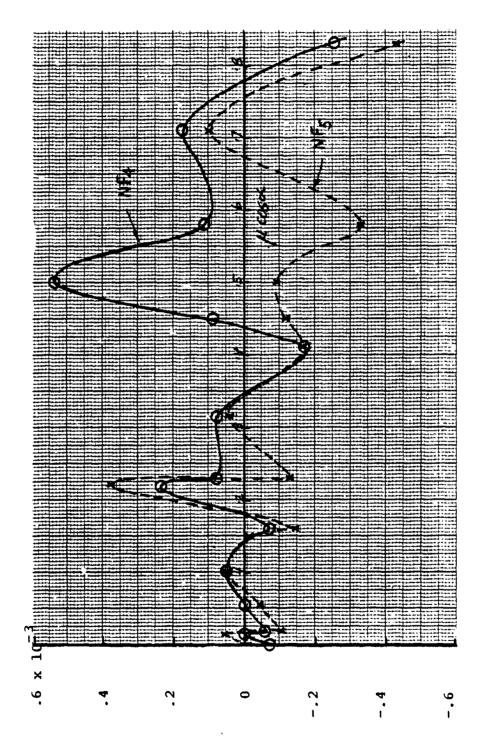


FIGURE A-2. COMPARISON OF MEASURED AND CALCULATED NORMAL FORCE COEFFICIENTS USING THE REGRESSION METHOD.



VARIATIONS OF COEFFICIENTS IN THE NORMAL FORCE EQUATION WITH $_{\mu}\text{COS}\alpha_{\star}.$ FIGURE A-3.

Introduction

As described in Section 1.0 an analysis was developed to help provide some guidance in choosing basic parameters for use in the regression approach. Later the analysis was expanded in the expectation that the analytical estimates could be simply related to the measured data and hence provide a means for predicting the rotor behavior. While this approach met with only limited success, the analysis and the results are presented here and may be used as a starting point for a more refined treatment. The objective was to obtain some closedform expressions for the rotor forces and moments that could be rapidly evaluated by a computer. Closed form was desired since the resulting expressions could be inspected to see the significance of each term and identify simplifications. The analysis is developed based upon the following assumptions:

- (1) uniform induced velocity across the disc
- (2) linear twist
- (3) constant blade chord
- (4' first flap bending mode only
- (5) no in-plane motion considered
- (6) no elastic torsion
- (7) linear section aerodynamics

Because the analysis must apply to a highly-twisted prop-rotor at large axial advance ratio, the conventional small-angle approximation to the inflow angle at a blade section cannot be made. This results in a very lengthy development of the analysis and the resulting equations are also lengthy. The treatment is an extension of that given by Dommasch in Reference 4 and makes use of some results presented in Reference 5. The final equations are presented in full with no simplifications made other than those stated. An assessment of the relative importance of each term was postponed.

The analysis is developed in rotor wind axes i.e., at zero sideslip and at a resultant angle of attack related to the wind tunnel pitch and yaw angles by

 $\alpha_{R} = \cos^{-1} (\cos \alpha_{T} \cos \psi_{T})$.

<u>ANALYSIS</u>

Referring to Figure B.1 let the deflected blade shape be represented by

$$Z = rC_0 + RSC_1)f(v)$$

where S(x) is the first flap bending mode shape and $f(\phi)$ is a first harmonic variation with azimuth i.e.

$$Z = r C_0 + R S(x) (a_0 - a_1 \cos \psi - a_2 \sin \psi)$$
 (2)

Taking moments about the blade root, the centrifugal, inertial and gravity forces acting on the element of mass dm yield

where \(\frac{1}{2} \) is the mass per unit length and \(\mathbb{A}_{\begin{subarray}{c} \text{is} \text{ the shaft angle measured from the horizontal.} \)

The aerodynamic contribution to the root moment is approximated by

The total externally-applied moment is therefore

and the existing elastic moment is

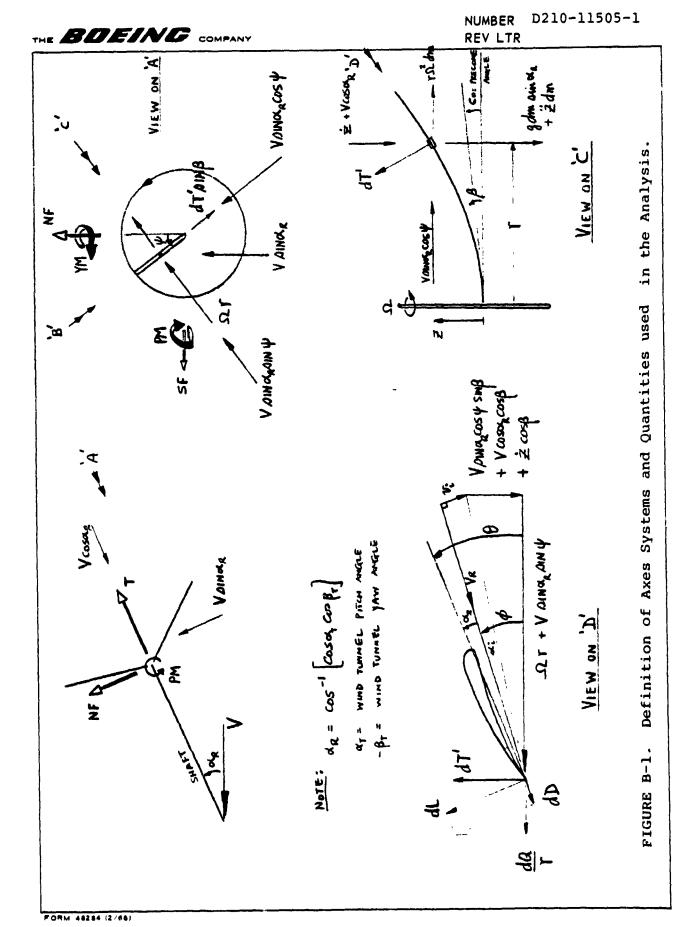
$$M_{a} = \left[E I \frac{d^{2}z}{dr^{2}} \right]_{r=0} = \left[E I R f(\psi) \frac{d^{2}s}{dr^{2}} \right]_{r=0}$$
 (4)

Now

$$dM_i = r \ddot{z} \rho' dr = \Omega^2 R f_i S \rho' r dr$$

$$dM_{i} = r \ddot{z} \rho' dr = \Omega^2 r \rho' dr (r c_0 + R S f_i)$$

where



$$\therefore dM_i + dM_{cf} = \Omega^2 R^3 \left[f_i S_x + x^2 C_0 + x^2 S_f \right] \rho^i dx$$

and
$$M_{I} = \int_{0}^{R} \left(\frac{dMi}{dr} + \frac{dMcr}{dr} \right) dr = \Omega^{2} R^{3} \left(a_{0} I_{1} + c_{0} I_{0} \right) (5)$$
where
$$I_{0} = \int_{0}^{1} \rho' x^{2} dx \quad ; \quad I_{1} = \int_{0}^{1} S \times \rho' dx$$

$$M_{W} = \int_{0}^{R} g r \sin u_{R} \rho' dr = M_{W} \sin u_{R} \qquad (6)$$

where Mw is the blade weight moment.

The aerodynamic contribution to the moment is now required. With reference to Figure B.1, assuming small angles for the induced inflow, the tangential and perpendicular components of velocity are

these components become

$$\tilde{U}_{P} = \lambda + (c_{0} + f S') \mu \cos \psi + S f_{3} = \tilde{V}_{R} \rho \dot{\mu} \phi$$

$$\tilde{U}_{T} = \mu L \dot{\mu} \psi + \chi \qquad = \tilde{V}_{R} \rho \cos \phi$$

FORM 46284 (2/66)

The elemental thrust is

$$dT = dL \cos \phi - dD \sin \phi \tag{9}$$

$$a = dC_2/dx$$

and
$$\alpha_{\ell} = \theta - \phi - \Delta \sin(\theta - \phi)$$
 for unstalled flow.

Therefore we have

$$dT = K_{T} \left\{ \tilde{U}_{T}^{2} \sin \theta - (1 + \mathcal{C}_{d}) \tilde{U}_{T} \tilde{U}_{p} \cos \theta - \mathcal{C}_{d} \tilde{U}_{p}^{2} \sin \theta \right\} dx$$
(10)

Where
$$K_T = \frac{1}{2} \rho a c \Omega^2 R^3$$

$$C_{ij}^{ij} = \frac{G}{4} a$$

This form for the thrust allows the high inflow conditions of the tilting rotor to be treated in a straightforward manner. When calculating the thrust force the drag contribution to the thrust will be retained since in high speed cruise this can be a significant portion of the total. For the present purpose of calculating the aerodynamic moment, however, the drag will be neglected.

The local value of blade angle, θ , is

$$\theta = \theta_0 - \theta_T \times - A, \cos \psi - B, \sin \psi$$

$$= \theta' - \Delta \theta$$
(11)

A, and B, are the lateral and longitudinal values of cyclic, $heta_{m{ extstyle e}}$ the root blade angle, and $heta_{m{ extstyle extstyle e}}$ is the net linear twist.

FORM 46284 (2/64)

Thus

for normal values of cyclic pitch,

The aerodynamic moment about the blade root at aximuth ψ is, therefore,

$$M_{\ell} = K_{\tau} R \int_{0}^{\ell} x \, dT \, dx$$

$$= K_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u}^{2} \psi + 2\mu x^{2} a \hat{u} \psi + x^{3} \right) - Ros \theta \right[$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \theta \hat{u} \right) + \mu x^{2} \hat{u} \hat{u} \psi + \mu x^{2} \hat{u} \hat{u} \psi + \mu x^{2} \hat{u} \hat{u} \psi \right]$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \theta \left(x \, \mu^{2} \psi + 2\mu x^{2} \hat{u} \psi + x^{2} \hat{u} \psi \right) + \mu x^{2} \hat{u} \hat{u} \psi + \mu x^{2} \hat{u} \psi \right]$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi \right\} + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi \right]$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi \right\} + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat{u} \psi \right]$$

$$= k_{\tau} R \int_{0}^{\ell} \left\{ \Delta u \hat{u} \psi + \mu x^{2} \hat{u} \psi + \mu x^{2} \hat$$

When performing the integration, integrals of the form

$$\int_{a}^{b} x^{n} \sin \theta' dx , \qquad \int_{a}^{b} x^{n} \cos \theta' dx$$

$$\int_{a}^{b} \frac{ds}{dx} \cdot S \cdot x^{n} \sin \theta' dx , \qquad \int_{a}^{b} S \cdot x^{n} \cos \theta' dx$$

are encountered. The following notation is introduced to represent these twist integrals.

Let
$$T_{nc}^{ij} = \int_{0}^{1} \left(\frac{ds}{dx}\right)^{i} s^{j} x^{n} \cos\theta' dx$$

$$T_{ns}^{ij} = \int_{0}^{1} \left(\frac{ds}{dx}\right)^{i} s^{j} x^{n} \sin\theta' dx$$

FORM 46284 (2/64)

where, for example, $T_{nc}^{00} = \int_{0}^{1} x^{n} \cos \theta dx$ $T_{3c}^{12} = \int_{0}^{1} \frac{ds}{ds} s^{2} x^{3} \cos \theta dx$

Now

$$T_{nc}^{ij} = \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \left(\cos \theta_{0} \cos \theta_{T} \chi + \sin \theta_{0} \sin \theta_{T} \chi \right) d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \sin \theta_{T} d\chi$$

$$= \cos \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} \cos \theta_{T} \chi d\chi + \sin \theta_{0} \int_{0}^{1} (\frac{ds}{dx})^{i} S^{j} \chi^{n} d\chi$$

Similarly
$$T_{ns}^{ij} = \text{LinO}_0 I_{nc}^{ij} - \text{CosO}_0 I_{ns}^{ij}$$
 (16)

The values of I_{MC} , I_{MS} are constants for a given mode shape

and twist.

With this notation equation (14) may be integrated. The resulting expression when simplified to include only steady and first harmonic terms is

$$\frac{M_{\psi}^{a}}{RK_{T}} = \frac{1}{2} \mu^{2} T_{15}^{00} + T_{35}^{00} - \mu B_{1} T_{2c}^{00} - \frac{1}{2} \mu a_{1} T_{1c}^{0} - \lambda T_{2c}^{00} + \frac{1}{2} a_{1} \mu T_{2c}^{0}}{-\frac{1}{2} \lambda \mu B_{1} T_{15}^{00} - \frac{1}{2} \mu c_{0} T_{25}^{00} A_{1} - \frac{1}{2} \mu a_{0} T_{25}^{10} A_{1} - \frac{1}{2} a_{1} B_{1} T_{25}^{0}}$$

FORM 46264 (2/64)

 $+ \frac{1}{2}a_{2}A_{1}T_{2s}^{0} - \cos\psi \left\{ \frac{1}{4}\mu^{2}T_{1c}A_{1} + A_{1}T_{3c}^{00} - \frac{1}{4}\mu^{2}a_{2}T_{1c}^{00} \right. \\ + \mu \cos T_{2e}^{00} - a_{2}T_{2c}^{01} + a_{0}\mu T_{2c}^{00} + \frac{1}{4}\mu^{2}\cos B_{1}T_{1s}^{00} + \frac{1}{4}\mu^{2}a_{0}B_{1}T_{1s}^{00} \\ + \frac{1}{4}\mu a_{1}A_{1}T_{1s}^{01} - \frac{1}{4}\mu a_{2}T_{1s}^{00}B_{1} + \lambda T_{2s}^{00}A_{1} - \frac{3}{4}\mu a_{1}A_{1}T_{2s}^{00} \\ - \frac{1}{4}\mu a_{2}B_{1}T_{2s}^{00} - au_{1}\psi \left\{ -2\mu T_{2s}^{00} + \frac{3}{4}\mu^{2}B_{1}T_{1c}^{00} + B_{1}T_{1s}^{00} + A_{1}T_{2s}^{00} + \frac{3}{4}\mu^{2}a_{0}T_{1s}^{00} + A_{1}T_{1c}^{00} + a_{1}T_{2c}^{01} + \frac{1}{4}\mu^{2}c_{0}T_{1s}^{00}A_{1} \\ + \frac{1}{4}\mu^{2}a_{0}A_{1}T_{1s}^{00} - \frac{1}{4}\mu a_{2}A_{1}T_{1s}^{01} + \frac{3}{4}\mu a_{1}B_{1}T_{2s}^{01} + \lambda T_{2s}^{00}B_{1} \\ - \frac{1}{4}\mu a_{2}A_{1}T_{2s}^{00} - \frac{1}{4}\mu a_{1}B_{1}T_{2s}^{00} \right\}$ (17)

Equating this expression for the aerodynamic moment to the moments due to inertia, centrifugal force, weight and elastic bending it is possible to obtain the coefficients a_0 , a_1 and a_2 of the first harmonic flapping by solving the following set of equations.

$$C_{4} A_{0} + C_{12} A_{1} + C_{13} A_{2} = R_{1}$$
 $C_{21} A_{0} + C_{12} A_{1} + C_{23} A_{2} = R_{2}$
 $C_{31} A_{0} + C_{32} A_{1} + C_{33} A_{2} = R_{3}$
(18)

where

$$C_{11} = \frac{\pi^{2} E I}{4R^{2} K_{T}} + \frac{\Omega^{2} R^{2} I_{1}}{K_{T}} + \frac{1}{2} \mu A_{1} T_{25}^{10}$$

$$C_{12} = \frac{1}{2} \mu \left(T_{12}^{01} - T_{22}^{10} \right) + \frac{1}{2} B_{1} T_{25}^{01}$$

$$C_{13} = -\frac{1}{2} A_{1} T_{25}^{01}$$

$$R_{1} = \frac{1}{2} \mu T_{15}^{00} \left(\mu - \lambda \beta_{1} \right) + T_{35}^{00} - \left(\mu \beta_{1} + \lambda \right) T_{22}^{00} - \frac{1}{2} \mu C_{2} A_{1} T_{25}^{00}$$

$$-\frac{M_{W}}{RKT} \text{ with } \alpha_{R} - \frac{\Omega^{2}R^{2}G}{K_{T}} \tilde{I}_{0}$$

$$C_{21} = -\mu T_{22}^{10} - \frac{1}{4} \mu^{2} B_{1} T_{25}^{10}$$

$$C_{22} = \frac{\pi^{2}EI}{4R^{2}K_{T}} - \frac{1}{4} \mu A_{1} (T_{15}^{01} - 3T_{25}^{10})$$

$$C_{23} = \frac{1}{4} \mu^{2} T_{12}^{10} + T_{22}^{01} + \frac{1}{4} \mu B_{1} (T_{15}^{01} + T_{25}^{10})$$

$$R_{2} = \frac{1}{4} \mu^{2} A_{1} T_{12}^{\infty} + A_{1} T_{32}^{\infty} + \mu C_{0} T_{22}^{\infty} + \frac{1}{4} \mu^{2} C_{0} B_{1} T_{15}^{\infty}$$

$$+ \lambda T_{25}^{\infty} A_{1}$$

$$C_{31} = -\frac{1}{4} \mu^{2} A_{1} T_{15}^{10}$$

$$C_{32} = \frac{1}{4} \mu^{2} T_{12}^{10} - T_{22}^{01} - \frac{1}{4} \mu B_{1} (3T_{15}^{01} - T_{25}^{10})$$

$$C_{33} = \frac{\pi^{2}EI}{4R^{2}K_{T}} + \frac{1}{4} \mu A_{1} (T_{15}^{01} + T_{25}^{10})$$

$$R_{3} = -2\mu T_{25}^{\infty} + \frac{3}{4} \mu^{2} B_{1} T_{12}^{\infty} + B_{1} T_{32}^{\infty} + \lambda \mu T_{12}^{\infty}$$

FORM 10284 (2/66

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Expressions for the Rotor Forces and Moments

Because of the very lengthy manipulations involved in obtaining expression for the rotor forces and moments, only the first few steps in each development will be given and then the final result will be presented.

Thrust

Retaining the drag contribution, the thrust on an element is, from equations (10) and (11), and neglecting squares and products of the flapping coefficients -

$$dT = K_{7} \left\{ \left(\text{Sind} - \Delta \theta \left(\cos \theta^{1} \right) \right) \mu^{2} \mu \dot{h}^{2} \psi + 2 \mu \kappa \mu \dot{h} \psi + \chi^{2} \right) \right.$$

$$- \left(1 + C_{4}^{2} \right) \left[\left(\cos \theta^{1} + \Delta \theta \right) \sin \theta^{1} \right) \left(\lambda \mu \sin \psi + \frac{1}{2} \cos \mu^{2} \right) \sin 2\psi \right.$$

$$+ \frac{1}{2} \mu^{2} \sin 2\psi + S^{2} + \mu S f_{3} \sin \psi + \kappa \lambda + \cos \mu \cos \psi \right.$$

$$+ \kappa \mu f S^{2} \cos \psi + \kappa S f_{3} \right] - C_{4}^{2} \left[\left(\Delta \mu \partial^{1} - \Delta \theta \cos \theta^{2} \right) \right] \lambda^{2}$$

$$+ \mu^{2} \left(\sigma^{2} \cos^{2} \psi + 2 \cos \mu^{2} f S^{2} \cos^{2} \psi + 2 \right) \cos \mu \cos \psi$$

$$+ 2 \lambda \mu f S^{2} \cos \psi + 2 \lambda S f_{3} + 2 \cos \mu \cos \psi S f_{3} \right] d\kappa$$

Integrating around the azimuth and along the blade the final expression for the thrust is

$$\frac{2CT}{GG} = \frac{1}{2}\mu^{2}T_{os}^{oo} + T_{2s}^{oo} - \mu B_{i}T_{ic}^{oo} - (\frac{1+CL}{2})\left[A_{i}\mu T_{oc}^{ol} + 2\lambda T_{ic}^{oo} - a_{i}\mu T_{ic}^{io} + B_{i}\lambda \mu T_{os}^{oo} - \frac{1}{4}\left(H_{i}A_{2} + B_{i}A_{i}\right)\mu^{2}T_{os}^{ic} + A_{i}C_{o}\mu T_{is}^{oo} + A_{i}C_{o}\mu^{2}T_{os}^{io} - A_{i}\lambda\mu T_{os}^{ol}\right]$$

$$- C_{d}\left[\lambda^{2}T_{os}^{oo} + \frac{1}{2}\mu^{2}C_{o}^{2}T_{os}^{oo} + a_{o}C_{o}\mu^{2}T_{os}^{io} - a_{i}\lambda\mu T_{os}^{io}\right]$$

FORM 40284 (2/64)

This equation is solved in the usual manner by using momentum theory to obtain a value of λ consistent with the thrust.

Rotor Power

At blade radius r the contribution of the element dr to the rotor power is

$$dP = \Omega + \left[dL \sin \phi + dD \cos \phi \right] dr$$

$$= K_T \Omega R \left[(I+G) \tilde{U}_P \tilde{U}_T \sin \theta - \tilde{U}_P^2 \cos \theta + G \tilde{U}_T^2 \cos \theta \right] x dx$$

Performing the same kind of substitutions, simplifications and integrations as were required to obtain $C_{\rm T}$, the final equation for rotor power coefficient is

$$\frac{2C_{9}}{\sigma a} = (I + GL) \left[\lambda T_{2S}^{\infty} + \frac{1}{2} a_{1} \mu \left(T_{1S}^{01} - T_{2S}^{10} \right) - \frac{1}{2} \lambda \mu B_{1} T_{1C}^{\infty} \right] \\
- \frac{1}{2} c_{0} \mu A_{1} T_{2C}^{\infty} + \frac{1}{8} \mu^{2} \left(a_{1} B_{1} + a_{1} A_{1} \right) T_{1C}^{10} - \frac{1}{2} \mu a_{0} A_{1} T_{2C}^{10} \\
- \frac{1}{2} \left(a_{1} B_{1} - a_{1} A_{1} \right) T_{2C}^{01} \right] + GL \left[\frac{1}{2} \mu^{2} T_{1C}^{00} + T_{3C}^{\infty} + \mu B_{1} T_{2S}^{\infty} \right] \\
- \lambda^{2} T_{1C}^{\infty} + \frac{1}{2} G^{2} \mu^{2} T_{1C}^{\infty} - a_{0} G \mu^{2} T_{1C}^{10} + a_{1} \mu \lambda T_{1C}^{10} \\
+ a_{1} G \mu T_{1C}^{01} + \frac{1}{4} G \mu^{2} \left(3a_{1} A_{1} + a_{1} B_{1} \right) T_{1S}^{10} - \lambda \mu G A_{1} T_{1S}^{\infty} \\
- \lambda \mu a_{0} A_{1} T_{1S}^{10} - \lambda \left(a_{1} B_{1} - a_{2} A_{1} \right) T_{1S}^{01}$$



Rotor Pitching Moment and Yawing Moment

In Reference 5 a particularly simple set of equations are obtained for the pitching moment and yawing moment coefficients in terms of the first harmonic flapping coefficients. Defining an analog of the Lock number as

$$S_{i} = \frac{\rho a c R}{\int_{0}^{i} \rho' S \times dx}$$
 (23)

the pitching moment coefficient is

$$\frac{2 \, C_{PM}}{\sigma a} = \left(\frac{\lambda_i^2 - 1}{\delta_i} \right) a_i \tag{24}$$

and the yawing moment coefficient is

$$\frac{2 C \gamma M}{\sigma a} = \frac{\left(\lambda_1^2 - 1\right) a_2}{\chi_1} \tag{25}$$

where λ_i is the (nondimensional) first flap frequency and the directions for positive moments are defined in Figure B-1.

Rotor Normal Force

Referring to Figure B-l the elementary contribution to the normal force at station r on a blade is

With the approximation

the normal force coefficient may be obtained (after some considerable labor) as the sume of file terms

$$\frac{2C_{HF}}{Ga} = \frac{2(N_{F})}{Va} + \frac{2(N_{F})^{2}}{Va} + \frac{2(N_{F})^{2}}{Va} + \frac{2(N_{F})^{2}}{Va} + \frac{2(N_{F})^{2}}{Va}$$

OPM 46284 (2 66

where

$$\frac{2C_{MPL}}{\nabla a} = \frac{(1+C_{L})}{B} \left\{ 4a_{1}T_{1S}^{ol} - 4\lambda B_{1}T_{1C}^{oo} + \mu \left[4\lambda T_{0S}^{oo} - a_{1}\mu T_{0S}^{io} - A_{1}\mu \left(\frac{1}{G} - \frac{1}{G} \right) + \left(A_{1}a_{2} - B_{1}a_{1} \right) T_{1C}^{io} - \left(3B_{1}a_{1} - A_{1}a_{2} \right) T_{0C}^{io} \right] \right\} \\
+ \frac{c_{1}}{B} \left\{ 4B_{1}T_{2S}^{oo} + \mu \left(8T_{1C}^{oo} + 3B_{1}\mu T_{0S}^{oo} \right) \right\} - \lambda \left\{ a_{1}T_{0c}^{ol} + \frac{3}{2}\lambda T_{0S}^{oo} \right\} \right\} \\
+ \frac{f_{1}}{4} \left\{ \left(A_{1}a_{2} + B_{1}a_{1} \right) \lambda T_{0S}^{io} - \left(A_{1}a_{1} - B_{1}a_{2} \right) c_{0}T_{0S}^{ol} + c_{0}\mu \left(a_{2}T_{0c}^{ol} - \frac{1}{2}B_{1}T_{0S}^{oo} - B_{1}a_{0}T_{0S}^{ol} \right) \right\}$$

$$\frac{2C_{MPL}}{\nabla a} = -c_{0} \left\{ \left(\frac{1+C_{1}}{B} \right) \left[4a_{2}T_{1C}^{ol} - 4\lambda A_{1}T_{1S}^{oo} + \mu \left(a_{2}\mu T_{0c}^{ol} - B_{1}\mu c_{0}T_{0S}^{oo} - B_{1}\mu c_{0}T_{0S}^{oo} \right) \right\} \\
- B_{1}a_{0}\mu T_{0S}^{io} - \left(A_{1}a_{1} - B_{1}a_{2} \right) T_{0S}^{ol} - 4c_{0}T_{1C}^{oo} + 2A_{1}\lambda^{2}T_{0C}^{oo} \\
+ \mu \left(3A_{1}a_{1} + B_{1}a_{2} \right) T_{1S}^{io} \right) \right] + \frac{c_{1}}{4} \left[4\lambda a_{2}T_{0S}^{ol} + 2A_{1}\lambda^{2}T_{0C}^{oo} \right] \\
- \frac{A_{1}}{a} \left(\mu^{2}T_{0C}^{oo} + 4T_{1C}^{oo} \right) \right\}$$

$$(27)$$

$$\frac{1 \, \text{CMP3}}{\text{Ta}} = a_0 \left\{ \frac{(1+\zeta_0^1)}{8} \left[4a_2 \, \text{T}_{1c}^{1} - 4 \right] A_1 \, \text{T}_{1s}^{10} + \mu \left(a_2 \mu \, \text{T}_{0c}^{10} - \frac{1}{6} \right) \right] + \frac{\zeta_0^1}{8} \left[4a_2 \, \text{T}_{1s}^{10} - 4 \right] A_1 \, \text{T}_{1s}^{10} + \mu \left(a_2 \mu \, \text{T}_{0c}^{10} - \frac{1}{6} \right) \right] + \frac{\zeta_0^1}{4} \left[4 \right] A_2 \, \text{T}_{1s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_2 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} - \frac{\zeta_0^1}{8} \left[4 \right] \left[4 \right] \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] \left[4 \right] \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1 \, \text{T}_{0s}^{10} + \frac{\zeta_0^1}{4} \left[4 \right] A_1$$

$$\frac{1}{\sigma a} \sum_{i=1}^{N} \left[\left(\frac{1}{B} \right) \left[\left(\frac{1}{B} a_{1} - A_{1} a_{1} \right) \right] \right] + \mu \left(\frac{1}{A_{1}} a_{1} + \frac{1}{2} \left(A_{1} a_{1} \right) \right] \\
+ \left(\frac{1}{B} a_{2} \right) \mu \left(\frac{1}{B} a_{1} \right) - \mu \left(\frac{1}{B} a_{1} \right) \left(\frac{1}{B} a_{1} \right) \left(\frac{1}{B} a_{1} \right) \right) + \frac{1}{B} \left(\frac{1}{B} a_{1} \right) \left($$

Rotor Sideforce

The elementary contribution to rotor sideforce is

and, as for the normal force, the sideforce is given by

$$\frac{2CsF}{\sigma a} = \frac{2CsF}{\sigma a} + \frac{2CsF}{\sigma a} + \frac{2CsF}{\sigma a} + \frac{2CsF}{\sigma a} + \frac{2CsF}{\sigma a} + \frac{2CsF}{\sigma a}$$

where

$$2\frac{c_{sfi}}{\sigma^{2}} = (1+\frac{c_{i}}{8}) \left\{ -4\frac{1}{A_{i}} \right\} T_{ic}^{oo} + \mu \left[4c_{o}T_{is}^{oo} - a_{b}\mu T_{os}^{io} + 44_{o}T_{is}^{io} \right]$$

$$-3_{i}\mu \left(c_{o}T_{oc}^{oo} + a_{o}T_{oc}^{io} \right) + \left(3A_{i}a_{i} + B_{i}a_{2} \right) T_{ic}^{io} - \left(A_{i}a_{i} - B_{i}a_{2} \right) T_{ic}^{or} \right]$$

$$-\frac{c_{i}}{8} \left[A_{i}\mu^{2}T_{os}^{oo} + 4A_{i}T_{2s}^{oo} \right] - \lambda \left[A_{i}\lambda T_{os}^{oo} - a_{i}T_{oc}^{oi} \right] + \frac{1}{2} \left[A_{i}\mu^{2}T_{os}^{oo} + 4A_{i}T_{2s}^{oo} \right]$$

$$\frac{\mu}{4} \left[(3A_{1}a_{1} + B_{1}a_{2}) \lambda T_{os}^{io} + (3A_{1}a_{2} - B_{1}a_{3}) c_{0}T_{os}^{io} \right] + c_{0}\mu \left(3a_{1}T_{oc}^{io} - \frac{3}{2}A_{1}T_{os}^{io} \right) - 3A_{1}a_{2}T_{os}^{io} \right] - \lambda\mu \left(c_{0}T_{oc}^{io} + a_{0}T_{oc}^{io} \right)$$

$$\frac{1}{2}C_{SF2} = c_{0}\left\{ (\frac{1+c_{0}^{4}}{8}) \left[-4a_{1}T_{ic}^{io} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{2}\mu T_{oc}^{io} - A_{1}c_{0}\mu T_{os}^{io} \right) \right] - A_{1}\mu \left(c_{0}T_{os}^{io} - A_{1}c_{0}\mu T_{os}^{io} \right) + c_{0}\left\{ a_{1}a_{2} - B_{1}a_{1} \right\} T_{is}^{io} - (3B_{1}a_{1} - A_{1}a_{1}) T_{os}^{io} - 4\lambda T_{oc}^{io} \right] + c_{0}\left\{ a_{1}a_{2} - A_{1}a_{1} \right\} T_{os}^{io} + c_{0}\left\{ a_{1}a_{1} - A_{1}a_{1} \right\} T_{os}^{io} - \lambda \left(A_{1}a_{1} + B_{1}a_{1} \right) T_{os}^{io} + c_{0}\left\{ A_{1}a_{1} - B_{1}a_{1} \right\} T_{is}^{io} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} - A_{1}a_{1} \right) T_{os}^{io} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} - A_{1}a_{1} \right) T_{is}^{io} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} - A_{1}a_{1} \right) T_{is}^{io} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} + A_{1}a_{1} \right) T_{is}^{ii} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} + A_{1}a_{1} \right) T_{is}^{ii} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{ic}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} + A_{1}a_{1} \right) T_{is}^{ii} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{is}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} + A_{1}a_{1} \right) T_{is}^{ii} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3} \left[-4a_{1}T_{is}^{ii} - 4\lambda B_{1}T_{is}^{io} + \mu \left(a_{1}\mu T_{os}^{ii} + A_{1}a_{1} \right) T_{is}^{ii} \right\} \right\} \right\}$$

$$\frac{1}{2}C_{SF3} = a_{0}\left\{ \frac{\left(1+c_{0}^{i}\right)}{3}$$

 $2\frac{c_{SP4}}{c_{TR}} = -a_1 \left\{ \frac{(1+c_4)}{8} \right\} \left(A_1 a_1 - B_1 a_2 \right) T_{15}'' + \mu \left(\frac{1}{2} \left(A_1 a_1 + B_1 a_2 \right) \right)$ μ Tos - λ A, Tos + a2 Toc + a2 Tiz - B, GTis - B1 40 T" - 1 co Toc - 1 ao T') + 4 1 1 (-a, co Tos + \(B_1 a \) \(\tau_{oc} \) + \(B_1 \) \(\co \) \(\tau_{oc} \) + \(a_2 \) \(\tau_{os} \) + \(\frac{1}{2} \) \((A_1 a_2 + B_1 a_1) \) copy Toc) + (Ajai - Bjaz) / Toc] - + Aj / Tic } $\frac{2\zeta_{SFS}}{\sigma a} = -az \left| \frac{(1+\zeta_{s}^{2})}{8} \right| \left(A_{1}a_{2} - 3B_{1}a_{1} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) \left(A_{1}a_{2} - 3B_{1}a_{1} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) \left(A_{1}a_{2} - 3B_{1}a_{1} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) \left(A_{1}a_{2} - 3B_{1}a_{1} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) \left(A_{1}a_{2} - 3B_{1}a_{1} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1c}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"} - 4\lambda T_{1C}^{"} + \mu \left(\frac{1+\zeta_{s}^{2}}{8} \right) T_{1S}^{"$ a, T" + 1 (Biai + Aiaz) / T" - 3A, T" - 3B, XT" - A, Co T's - A, ao T's)] + 4 (3 B, a, -A, a)) T' -2 x Tos + / (a, x Tos - acco / Tos + az co Tos + AIX (co T'oc + ao Toc) + 1/2 (AIAI + BIAL) COM Toc) + 3/4 (/4 T 05 - 2 B, T 10) + 1 T 10 }

SHEET B-17

Comparison of the Analytical Predictions with the Wind Tunnel Data

At each wind tunnel test point, the test values of collective pitch, cyclic, shaft angle of attack, yaw angle, advance ratio and rpm were used in the analysis to calculate the rotor forces and moments. The first flap bending mode shape was computed using the model blade properties presented in Reference 3. The frequencies of the first flap bending mode were obtained from the rotating blade frequency measurements given in that Reference. The average value of blade drag coefficient, Cd, was obtained by extrapolation of the hover power coefficient to zero thrust and using the approximation

$$C_{d} = 8C_{p_0}/\sigma \tag{36}$$

The results are presented in Figures B-2 through B-6 which show the calculated and measured forces and moments. The calculated values are plotted using the same symbol as the test value but marked by a flag. A guide to the test runs is provided in Tables B-1 and B-2.

In general the predictions are in fairly good agreement with thetest data considering the simplifying assumptions that are made in the analysis. In cruise flight the predicted slope of sideforce coefficient with collective pitch is opposite to the test data. This may indicate the need for a lead-lag degree of freedom in the analysis. Further work is required in this area. It should be noted that the execution time of the program incorporating the analysis is short, about the same as the curve-fit equations.

It was hoped that the analytical results would be linearly related to the measured data i.e.

$$C_{\text{F}} = a + b C_{\text{F}}$$
TEST
(37)

where a and b would be functions of effective advance ratio, $\mu\cos\alpha$. If this had been the case, then estimated values for the rotor forces could be obtained from

$$C_{F_{TEST}} = \frac{1}{b} (C_{F_{THEORY}}^{-a})$$
 (38)

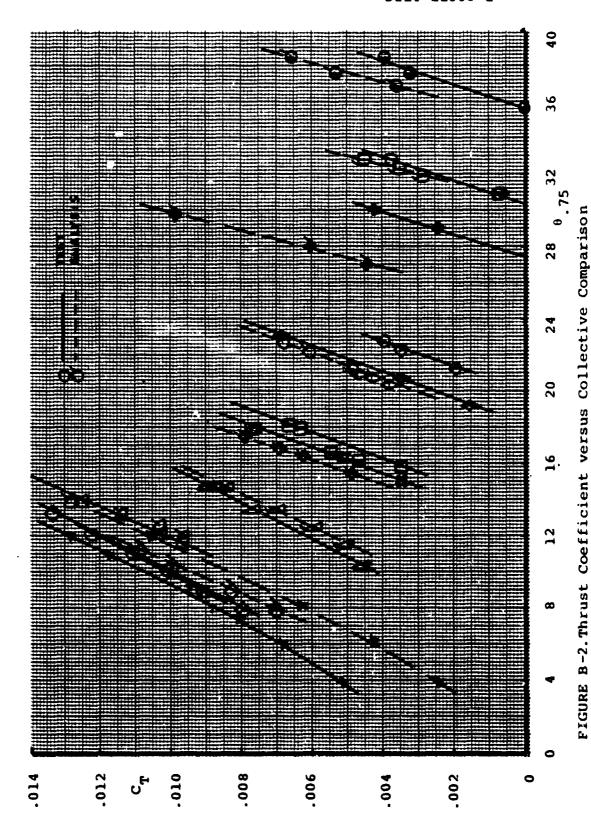
In other words the analysis would be used to predict the forces and moments, and equation (38) used to correct them to provide estimates. While linear relationships were found for thrust and power, the remaining quantities were not linearly related and the approach was abandoned in favor or direct curve fitting as described in Section 3.0.

RUN #	SYMBOL	RUN TYPE	μ	α	RPM	θ.75
27.28	*	⁰ ⋅75	0	90.	1185	10.0
39	0	α	.1	VARY		7.9
42		Ψ.	1	90		8.2
43	\Diamond	θ.75		80	•	VARY
45	Δ	RPM			VARY	8.9
46	4	α		VARY		
50	0	Ψ		8.2		
51		₩.75		1	1	VARY
51 53	0	RPM		•	VARY	8.9
54		α	.226	VARY	ı	13.5
55	0	Ψ	1	65		13.5
58		₹.75				VARY
59	- A	RPM			VARY	13.5
61	Ö	α.		VARY	7,11(2	16.0
62	O	ψ .		49.0		16.0
	Ħ	θ.75	-	1	-	VARY
63	$\overline{\nabla}$	RPM	VARY		VARY	16.0
68	7	α	.315	VARY	1	22.6
69	1 0	W W	•3+3	42.0		22.6
72	0	θ.75		1 1		VARY
74	8	RPM		 	VARY	22.6
	\ \ \ \			VA DV	VARY	
75	 	α		VARY		18.2
76	<u> </u>	ψ.75		59		18.2 VARY
79			· · · · · · · · · · · · · · · · · · ·		VARY	18.2
81 82	Φ	RPM	VARY	VADV	VARI	12.10
83	 •	a u	.226	VARY		
	<u> </u>	θ.75	-	76.0		12.10
86	<u> </u>		773 DV		****	VARY
88	<u> </u>	RPM	VARY	V	VARY	12.10
89	•	α	.252	VARY	1065	20.7
90	Φ	<u> </u>		26		20.7
93	<u> </u>	₹.75	***	ļ	V	VARY
95	<u> </u>	RPM	VARY	V	VAKY	20.7
96	<u> </u>	α	.351	VARY	 	29.0
97	10	Ψ		 	<u> </u>	29.0
100	- 25	₽.75	1	ļ	Y	VARY
102	**	RPM	VARY	<u> </u>	VARY	29.0
111		α	.451	VARY		32.0
112	4	Ψ		24.0		32.0
115	<u> </u>	θ,75	T	 		VARY
117	Φ	RPM	VARY	V	VARY	32.0
118	Φ	<u>a</u>	.510	VARY	946	36.0
119	1 4	ψ		13		36.0 36.0
123 125	0	θ.75	Y	 	7	36.0
125	<u> </u>	RPM	VARY	•	VARY	37.5
128	•	α	.58	VARY	830	41.5
132	_ A	Ψ	.58	0		41.5
138		Q.	.707			47.2
141		Ψ	.707			47.2
146	0	α	.836			52.0
148	•	Ψ	.836	1		52,0
153	<u> </u>	α	,97	0	830	56.3
154	0	Ú	.97	I	l l	56.4
					-	
159	A	α	.448	1 1	1 1	33.8

TABLE B-1. List of Runs in which Cyclic was Fixed B-19

D	CITADOS	RUN	İ			
RUN #	SYMBOL	TYPE	μ	α	RPM	⁰ .75
29	0	Al	0	90.0	1111	10.0
31		Bl	0	90.0	1110	9.9
32	\Diamond	Bl	0	90.0	1110	11.8
40		Bl	.1	80.0	1183	7.9
41		Al	.1	79.3	1183	8.0
84		Al	.23	76.0	1185	12.0
85		Bl	.23	76.0	1186	11.9
46	Q	Bl	.09	82.2	1186	8.6
49		Al	.1	81.7	1185	9.0
56	\bigcirc	Al	.23	64.0	1185	13.3
57		Bl	.23	63.5	1185	13.4
77		Al	.32	59.5	1184	18.0
78	0	Bl	.31	60.0	1185	17.9
64	O	Al	.23	48.6	1185	16.0
65		Bl	.23	48.6	1195	16.3
70		Al	.31	42.0	1186	22.5
71		Bl	.31	41.8	1185	22.6
91	0	Al	.25	31.0	1065	20.7
92	. 🔿	Bl	.25	31.0	1065	20.8
98	\Box	Al	. 35	26.5	1065	29.0
99		Bl	. 35	26.5	1065	29.0
113	0	Al	.45	24.3	1065	32.0
114		Bl	.45	24.3	1066	31.9
120	Φ	Al	.51	12.8	943	37.7
121	Δ	Bl	.51	12.7	944	37.6
122	8	Bl	.51	12.9	945	37.7
163		Al	.45	14.0	830	34.1
164	Φ	Bl	.44	13.7	830	33.6
133	Φ	Al	.58	15.0	830	41.8
134	Φ	Bl	,58	14.3	830	41.7
142	Φ	Al	.71	14.5	830	47.0
143		Bl	.71	14.5	830	47.1
149	0	Al	. 84	14.3	830	51.8
150	0	Bl	.84	14.0	828	51.9
155	\$	Al	.97	14.4	827	56.2
156	88	Bl	.97	14.7	826	56.3

TABLE B-2. List of Runs in which Cyclic was Varied



B-21

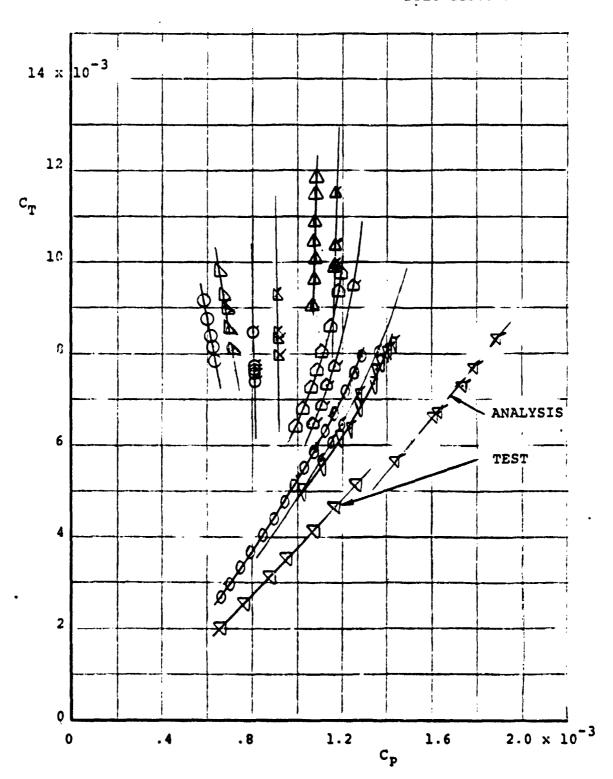


FIGURE B-3. Predicted and Measured Thrust Power Relationship during Shaft Angle Sweeps.

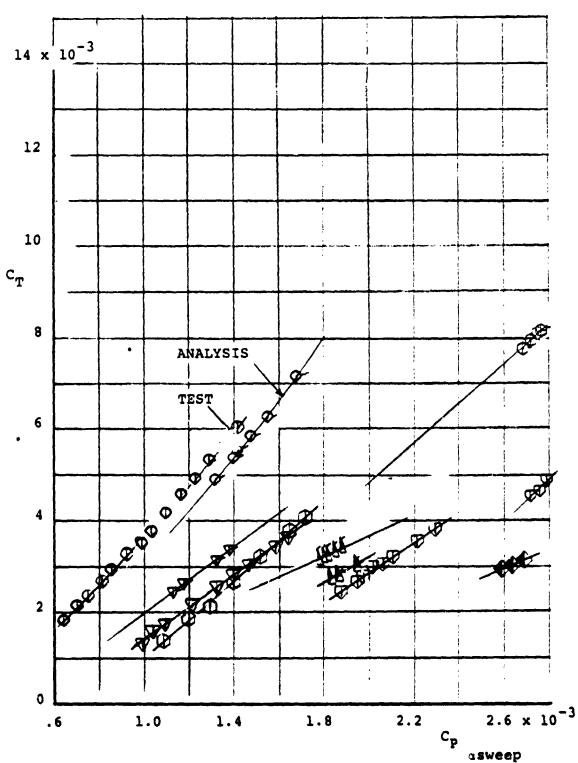


FIGURE B-3. Predicted and Measured Thrust Power Relationship during Shaft Angle Sweeps (Concluded)

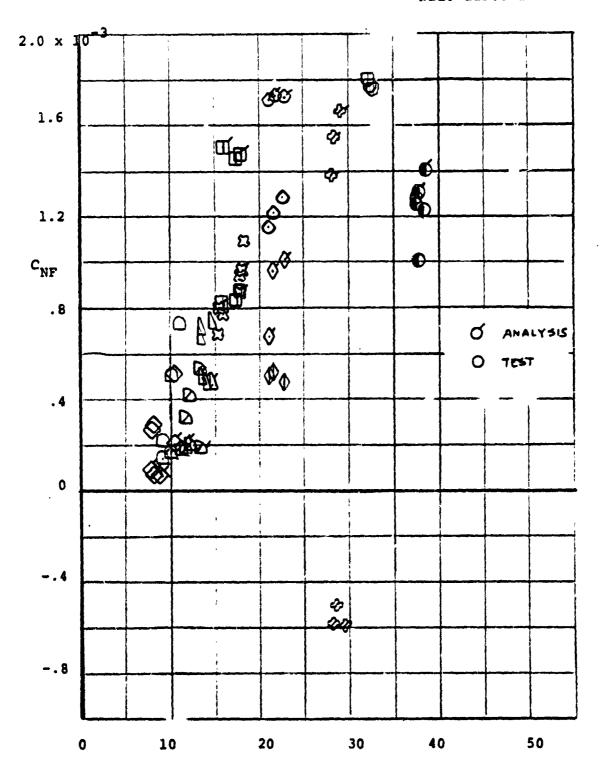


FIGURE B-4. Variation of Normal Force with Collective Pitch - Predicted vs. Test.

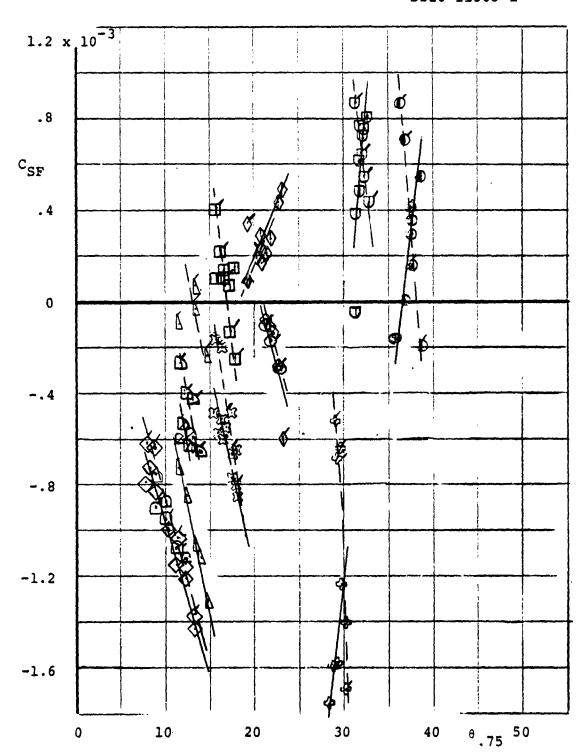


FIGURE B-5. Predicted and Measured Variations of Sideforce with Collective Pitch.

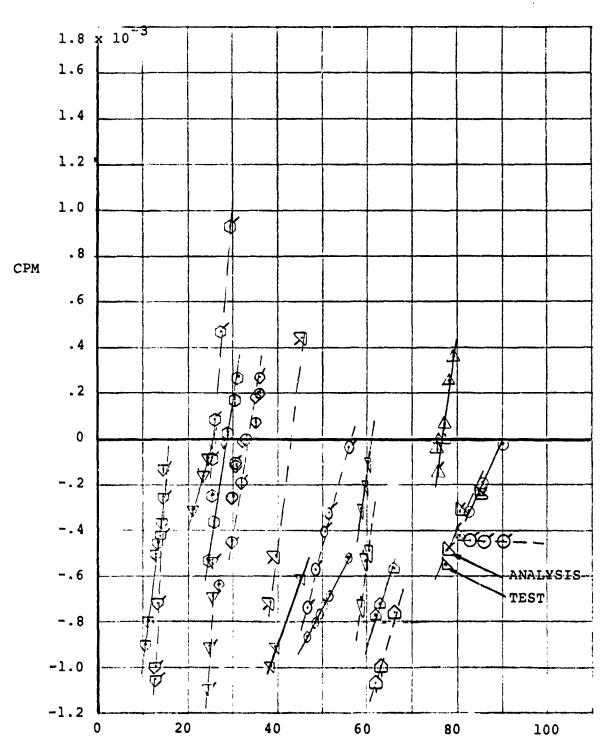


FIGURE B-6. Comparison of Predicted and Measured Pitching Moments during Shaft Angle Sweeps.

APPENDIX C. LISTING OF THE ROTOR MATH MODEL SUBROUTINE

			00000010
,	IC^F+CSF+CFM)		000000020
	DIMENSION X(8.5.8)		00000030
C****	CALC ESTIMATED VALUES OF FORCES AND MOMENTS ********	-	00000040
	DC 333 I=1.8		00000050
	En 333 J=1+5		00000060
•	00 333 K=1-8		00-000070
333	X(I+J+K)=0+0		00000060
	X(1.1.1)=4606		30000090
	X(1+1+2)=-4+7883		00000100
	Y(1.1.3)=-274.5361		00000110
	Y(1.1.4)=1199.8286		00000120
	x(1+1+5)=+1752-2216		00000130
	X(1.1.6)=996.5716		00000140
	y(1.1.7)=-165.1875 .		00000150
	x(2-1-11=-0353		-00000160-
	y (2 • 1 • 2) = 1 • 4 9 5 5		00000170
	X(2.1.3)==21.6829		00000180
	x(2-1-4)=20-5443		00000190
	X(3.1.1)=-1.3713		00000200
	X(3+1+2)=16+9001		00000210
	x(3-1-3)==210-3956		-00000220
	X(3.1.4)=E17.6291		00000230
	x(3.1.5)=-503.7611		00000240
	\(1\cdot 1\cdot 1		00000250
	x(4.1.1) = .7213		00000260
	x(4.1.2)=10.8416		30000270
	X(4-1-3)==176-0940		-00000260
	x(4,1,4)=686,3241		00000290
	x(4,1,5)=-823.1688		00000300
	x(4-1-6)=320-6294	-	0000031C
	x(5,1,1)=-,9261		00000320
	y(5,1,2)=-19.6913		00000330
	X (5+1+3)=116+0657		-00-000340
	x(5.1.4)=-150.7721		00000350
	X(5.1.5)=60.8424		00000360
	X(6+1+1)=3-C0R2		90600370
	x(6.1.2)=7260		00000380
	x(6.1.3)=66.1302		00000390
*	X(6+1+4)=-199-5429		00000400
	y(6.1.5)=203.5398		00000410
	x(6.1.6)=-70.6067		00000420

OF POOR QUALITY

x(7,1.1)=21.6525	00000430
x(7,1,2)=80.9658	20000440
7(7,1.3)=-10.2575	00000450
x(7.1.6) == 377.493C	00000460
y(7,1,5)=234,4536	00000470
x(8,1,1)=6.7245	03000480
X(6.1.21=4.755c	80000490
x(8.1.3) =-141.7667	00000500
X(E+1+4)=463+9147	30000510
X(&=1=5) ==327.1767	
×(1,2,1)=1416	00000530
x(1.2.2) =-57.3749	00000540
X(1+2+3)=247.9659	00000550-
X(1+2+4)=-460-4381	00000560
Y(1,2,5)=399.6938	00000570
X(1.2.6)==131.9327	
Y(2,2,1)=.0267	00000590
X(2,2,2)=-2.6925	
¥(2•2•3)≈•8550	00000610
y(2,2,4)≈-14.8580	00000620
X(2.2.5)=17.1088	00-000630
X(3,2,1)≈-1.4225	00000640-
y(3+2+2)=5+1466	00000650
x(3+2+3)==27-4211	
X(4+2+1)=-1+2323	00000670
x(4+2+2)=1.7646	00000680
X(4+2+3)=-48+9664	00-000690
x(4+2+4)=63.0376	00000700
X(4,2,5)=-28.463E	00000710
X(5+2+1)==3+2124	00000720
X(5+2+2)=-5.1175	00000730
x(5,2,3)=-11.7354	00000740
x(5+2+4)=43.8952	00000750
x(5,2,5)=-26.7432	00000760
X(6+2+1)=-+9117	00000770
X16+2+21=-17.3490	
x(6,2,3)=106.6433	00000790
x(6,2,4)=-122.5828	00800000
×16+2+51=40+0669	00000810-
X(7,2,1)=22.9366	00000020
X(7,2,2)=43.8971	00000833
X(7.2.3) = 267.0537	00000840
X(7,2,4)=-257.9979	00000850
×(8.2.1)=3.3847	00000860
X(8+2+2)=104-3205	00000870
X(8,2,3) =-854.6753	08800000
X(8,2,4)=2363.6418	00000890
X(8+2+5) =-2457-6914	00000500-
x(8,2,6)=907,4531	00000910
X(1+3+1)=-0.0711	00000920
×11+3+21=145-2747	00000930.
X(1.3.3) =-1732.9126	00000940
•	

	•
> (1.3.4) = 8 t 0 0.8 4 7 4	0000-
X(1.5.5)=-21977.7951	0300096
¥(1•3•€)=2Fb02•0645	0000097
x(1.3.7)=-14489.1633	0000098
x(1+3+6)=+15489+1633 *(1+3+6)=4752+5470	
x(2,3,1)=.0110	0000100
X(2.3.2)=1.6510	0000101
x(2+3+3)=8+5067	0000102
Y(2.3.4)=38.1397	0000103
X(2+3+5)=+220+2950	3000104
X(2+3+6)=287+7375	0000105
x(2.3.7)=-115.7626	0000106
X(3.3.1)=.2653	9000107
x(3+3+2\=-7+5021	00 CO 1 O F
X(3.3.3)=34.2657	9000109
X(4.3.1)=0117	0000110
¥(4-3-2)==E-5953	
x(4,3,3)=78.4126	0000112
x(4·3·4)=-157·1991	0000113
x(4+3+4)=-157+1991 x(4+3+5)=74+9577	0000114
Y(5.3.1)=.3494	0000115
X(5+3+2)=4+5443	0000116
-x(5+3+3)=-7+2098	0000117
X((+3+1)=+0579	0000118
Y(6,3,2)=6,2519	0000115
X(6+3+3)=-56+6109	0000126
x(6.3.4)=67.8128	0000121
x(6+3+5)==25+6700	000122
x(7,3,1)=2,1864	0000123
x(7+3+2)=40+1364	0000124
X(6+3+1)=1-2924	
x(8,3,2)=39,4773	0000126
x(8,3,3)=-308.0650	0000121
. x(8+3+4)=846+3157	
)(R ₁ 3.5)=-978.8486	0000129
λ(8·3·6)=446·9769	0000120
X(3-4-1)=-0208	
x(3,4,2)=2,6330	0000132
X (3.4.3) =-28.2534	0000133
X(3-4-4)=49-6782	
y(3.4.5)=-11.0460	0000135
y(4,4.1)=.1416	0000136
-X(4+4+2)=-5+0626	- 00-00137
x(4,4,3)=33.9888	0000138
Y(4.4.4)=-1G.3021	0000139
. X(5,4,1)=-0525	0000140
X(5,4,2)=-2.9718	0000141
Y(5,4.3)=29.7889	9000140
× (5 + 4 + 4) = -32 + 8614	
X(5,4,5)=10,4779	2000144
Y(6+4+1)=+1063	0000149
\((6+4+2)=5-33A2	

y(E+4+3)==12.0d92	00001470
x(6.4.4)=2.3666	00001480
y(7.4.1)=.0360	
y(7,4.2)=48.3816	00001500
X(7,4,3)=-93,3694	00001510
x(7,4,4)=393.3716	00001520
x(7.4.5)=-628.1853	00001530
x(7,4,6)=293,2343	00001540
x(8,4.1)=0301	
y(6.4.2)=6.6261	00001560
y(E,4.3)=-23.E374	00001570
x(8.4.4)=8C.2836	
x(8,4,5)=-38.1702	00001590
X(1.5.2)=.94	00001600
X(2.5.1)==.00.097	
x(2.5.2)=+.00784	00001620.
X(2.5.3)=0.89403	00001630
x(3.5,1)=.00016	00001640
y(3.5.2)=.02342	00001650
x(3.5.3)==1.12935	00001660
x(3.5.4)=1.71225	
x(3,5,5)=74232	00001680
X(4,5,1)=.00055	. 00001690
x(4.5.2)=01219	00001700
x(4.5.3)=-5.26963	00001710
x(4, f, 4) = 46.19188	00'001720
X(4.5.5) == 126.23074	
y(4.5.6)=141.12570	00001740
x(4.5.7)=-55.68757	00001750
x(5,5.1)=-0.0010	0.001.770
x(5.5.2)=09926 x(5.5.3)=.12484	00001770
X(5,5,5,3)=,12484	
X(5,5,4)=05549	00001790
X(E+5+1)=+0005283	00001800
X(6.5.2)=.1723509	
x(6.5.3)=7342283	00001820
x(6,5,4)=1.6377934	00001830
×(6+5+5)=-1-7332042	
x(6,5,6)=.6787662	00001850
C+++++ NOW FORM DERIVS WRT Al+Bl+ALFA+PSI+ETC ******	00001860
WEAMUP	00001860
CT41=GK(X+Z+1+1) 	00001890
CNFA1=GK(X+Z+3+1)	000C1910 00001920
じっしゅ イサバレ イン・マー・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・	
CPMA1=OK (X+Z+5+1)	00001940
CYMA1=GK(X+Z+6+1)	00001940
CPMA1=GK(X+Z+7+1)	
	00001970
CTE1=GK(X+Z+1+2)	00001970
CPE1=GK(X+Z+2+2)	00001380

00002500

```
CAF61=GK (X+Z+3+2)
                                                           00001990
 CSFF1=8+ (Y-Z-4-2)
                                                           00002000
 CP1 -1 =( + ( x + Z + 5 + 2 )
                                                           00002010
 CYM51=08 (X+2+6+2)
                                                           00002020
 C9*+1=CK (X.Z.7.2)
                                                           00002030
 FEM: 1#98 (X+Z+8+2)
 CTALF=G* (X+2+1+3)---------
                                                        -- - 00002050
 CPALF=GK(x+Z+2+3)
                                                           00002050
 CNEALF=(K(X,Z,3,3)
                                                           00002070
 CNFALF=AHS(CNFALF) ...
                                                           00002988
 CSFALF=GK(X+Z+4+3)
                                                           00002090
 CF"ALF=GK(X+Z+5+3)
                                                           00002100
 CYMALF=GK-(X+Z+6+3)....
                                                        - ---- 00002110
 CE YALF=(K(X+Z+7+3)
                                                           00002120
 FEMALF=GK(X+Z+8+3)
                                                           00002130
 CTFGI=GK(X+2+1+4)--- .... 00002140
 CFPSI=GK(X+Z+2+4)
                                                           00002150
 CAFPSI=GK(X+Z+3+4)
                                                           00002160
 CPMPSI=0K(y+Z+5+4)
                                                           00002180
 CY"PSI=RK(X+Z+6+4)
                                                           00002190
 00002200
 FRMESI=RK(Y+Z+8+4)
                                                           00002210
 CTPPM=CK(X+Z+1+5)
                                                           00002220
 --- 00002236
 CAFEPM=OK(X+Z+3+5)
                                                           30002240
 CSFRPY=GK(X+2+4+5)
                                                           00002250
 00002260
 CYMRPM=GK(X+Z+6+5)
                                                           00002270
 CEMRPM=GK(X+Z+7+5)
                                                           00002280
FEMFFM=GK(X+Z+8+5)
***** NOW CALCULATE REFERENCE VALUES OF ALPHA ******
                                                           00002290
                                                           00002300
 ALFFEF=F9.7176+Z+(-322.8042+Z+(770.9108+Z+(-1446.3424+Z+
                                                           00002313
1(1449.9018+Z+(-545.1154))))
                                                           00002320
 SYLFAC=1.0
                                                           00002330
 REYERFY+SKLFAC
                                                           00002340
 00002350
 GFMREF=1165.-(1185.-830.)*(1.-EYENAC/4R.)
                                                           00002360
 IF (EYENAC-GT-45-) RPMREF=1185--- -
                                                           00002370
 DELR-PM=RPM-RPMREF
                                                           00002380
 CELAI=AITST-5.0
                                                          00002390
 BELEI=BITST=5-C
                                                        - - -0000240C
 DELALF=ALPHR/DTR-ALFREF
                                                           70002410
 CELFSI=-EETAR/DTR
                                                           00002420
 ABSI=ABS (CELALEL _____
                                                           00002430
 ASS2=ASS(DELPSI)
                                                           00002440
 CELCT=(CTAI+CELAI+CTBI+DELBI+CTALF+CELALF+CTPSI+ABS2+CTRPM+
                                                           00002450
-1DELRENAZIOGOG-
                                                          · 90002460
 CELCP=(CPA1+DELA1+CPB1+DELB1+CPALF+DELALF+CPPSI+A5S2+CFRPM
                                                           00002470
1 * CEL PFM) / 10000.
                                                           00002460
 CELCNF=(CNFA1+BELA1+CNFB1+BFLB1+C%FALF+BELALF+C%FAS1+BELPS1 -
                                                           00002490
1+CNFRFM+DELFPM)/10000.
```

	2-30 3300,2	
	DELOSF=(OSFA1*DELA1+OSFE1*DELF1+OSFALF*CELALF+OSFPS1*DELPST	
	1+CSFRPN*CFLRPM)/10000	
	DELCEM#(CEMA1*DELA1+CPMR1*DELE1+CEMALE*PELALE+CEMPSI*DELPSI	
	1+CFT RPM+DELFPM)/10000.	00002540
	DELCYM=(CYMA1*DELA1+CYMB1*DELR1+CYMALF*CELALF+CYMPSI*DELPSI	
	1+CYMRPM+DELRPM)/10000.	00002560
	DELCRN=CHMA1*CELA1+CRMB1*DELB1+CHMALF*ARS1+CBMPSI*ABS2	00002570
	- 1+CETRFK+CELRPM	
	DELFAY=FBMA1*DELA1+FBM01*DELB1+FBMALF*ABS1+FBMPS1*ABS2	00002590
	! +FE%PPM*DELPPM	00002600
	IF (7.LT.C.615) -GO -TG. 30	
	IF(2.LT.0.055) GC TO 31	00002620
	IF(Z.LT.0.100) GO TO 32	00002630
-	IF(7.LT.0.147)_GC_TO_33	00-002640
	IF(2.LT.0.162) GO TO 34	00002650
	IF(Z.LT.0.210) GO TO 35	00002660
	IF.CZ-LT-0-23C1 GO.TG.36	
	IF(Z.LT.0.234) GO TO 37	00002680
	IF(Z.LT.0.410) GO TO 38	00002590
	IF(Z.LT.C.457) GG TO 39	00002700
	GC TC 40	00002710
30	GRAS1=11.933	00002726
	CEFT1==882	00002730
	GRAD 2=106.667	00002740
	CEFT2=-1.5	00002750
	GFAC3=267	
	CEPT3=.094	00002773
	GRAD4=-9.667 CEFI4=.035	00002780
	CEFT4=.035	00002790
	GC TC 41	00002800
31	GF AD1=3.175	00002810
*****		00002820
-	GRAC2=92.75	00002830
	CEFT2=-1.291	00002840
	GRAD3=.225	
	CEFT3=.087	00002860
	GRAC4=5.5	00002870
		00002880
	GC TC 41	00002890
32	GRAC1=1.467	00002900
~	. CEF 1121.107	
	GRAD 2=77.556	00002520
	CEPT2=456	00002930
	GRAD3=.E78	00002540_
	CEFT3=.067	00002950
-	GRADA=1-1-1-	00002960
	CEFT4=.G49	00002970
	GC TO 41	00002980
33		
	CEPT1=1.333	00003000
	GFAC2=85.106	00003010
	CEFT2=-1.211	

7			D210-11505-1	
4		GRAC#=.957		00003030
		CEFT3=.629		00003040
7		G=4[4=1+702		000030503
4		CEFT4=010		000030507
4		SC TO 41		00003070
	34	GRAD1=10-4		- 20003070
T	34	CEFT1=312	Biochemistres reminde the implement to the district as the second a second of the second contract and addissimate and the second contract as the second contract and the secon	00003090
*		GR4D2=193.333		00003100
		CEFT2=-17.12		00003110
7		GFAU3=733	ամանա գնացանանակումով#Ե հեռու չչարը։ Վուսագել ու շու այ պե որ հասանիքի պիտու ի առառ և այլ չչ և չչ։	30003110
Į		CEFT3=.276		
		CRAD4=-10-		00003130
	• •	CEPT4=1.71	effect over new megfinesshare of many not to the state to the to the state of the state of the state of the state of	00003140
T		GO TO 41		00003150
1,	35	- GR461==2-563		30003160
	.) 3	CEPT1=1.768	The state of the s	- 0000317 0
T		GRAD2=45.833		20003190
1		CEF12=6.775		00003200
•		GFAE3=1.479	The second secon	00003210
-		CEPT3=081		00003210
		GRAC4=4-125	· ·	00003230
á.		CEFT4=-1.226		00003240
		GC TO 41		00003250
7	36	GRACI=1-150	AND THE RESIDENCE OF TH	.00003260
1.		CEPT1=1.009		00003270
		GRAC 2=-40.		00003280
3.		CFPT2=24-8		00003290
1.		GRAC3=1.	•	0052000
4.		CEFT3=.020		00003310
		GRAD4=1	AND THE RESIDENCE TO THE RESIDENCE THE RESIDENCE OF THE RESIDENCE OF THE RESIDENCE THE RESIDENCE OF THE RESI	00003320
1		CEPT4=780		00003330
1.		GC TO 41		20003340
	37	- GRAC1=52-5	anterior a professional designation and the second	00003350
1.		CEPT1=-10.802		00003360
1		GRAL 2=1125.		00003370
	•	CEFT2==243+15	gad des allandes applies musicalistat est anno de la capa de 2 de la capa de 2 de la capa de 2 de la capa de 2	00003350
7-		GRAD3=+10+		00003350
1		CEPT3=2.55	·	00003460
4	•		Taxanananananananananananananananananana	
		CEFT4=24.463		00003420
T		SC TO 41		00003430
1	30	CEFT1=1.249	nder transport der grott der gemenkelter im der den der Standeren in stande transport der der der der der der d	00003440
		GRAD2=61-8182		00003450
7			- Company of the control of the cont	00003460
1	•	GFAD3=1.364	and the state of t	-
		CEFT3=109		00003460 00003490
			and the second s	00003498
4		CEPT4=.006	paramagas dan 1 y settingah ini gari 1900 kaca 2 - mar pendapa yan 1900 - yahar 1 1900 - 1 yang 2 1 1900 -	00003510
4		GC 70 41		00003520
	39		erandone e en en en en en en en en en en en en	00003530
T	5.2			00003540
1.		On.		30000044
		OF A MI	C-7	
I.		ORIGANAL PAGE IS		
.]		OF PLOR PAGE IS		
		717		

00003680

00003750

GC TG 41 - ---40 GFAT1=1.+795 00003620 CEFT1=1.0901 00003630 CEFT2=10.5759 GFAP3=.68 00003663 FFAC4=.793

GRACET.88

GRAJ4=.793

CEPT4=-.005 00003690 ---000063700 CELTCT=GRAD2+Z+CEFT2 00003710 GFAC CP=GRAD3+Z+CEFT3 00003720 IF(W.GT.0.51) GO TO 21 00003740 CEFCNF=-1.4499+W+(1.1164+W+(46.1585+W+(46.1533+W+(-4118.7472

1))))))) 00003770 CEFCNF=CEFCHF/1000. 00003760 10141+W*(-1043.6643+k*(520.6263+W*(1029.2775+W*(-966. 13633))))))) ____CO__TO _22.____ -----09003520 21 CEFCNF=(.35-35.79*(h-.51))/1000.

- ...1+k*(27714+8692+W*(-74786+6559+b*(89304+8015+W*(-39318+3083---------------00003760

GRDCNF=.0304667-.26494*(W-.51) IF CW.GI-C-6251 GRCC1F=0----- - -**-00003**850 22 IF(W.GT.0.50) GO TO 23 CEPCSF=-.3184+W*(31.8306+W*(-457.3674+W*(4745.5645+W*(-3 00003870 166x9.2177+4*(170991.2286+W*(-441355.4596*A*(580754.... 1.9029+W+(-303701.0909))))))) 00003890

GO TO 24 CEPCSF=CEPCSF/1000. 00003920 IF(w.GT.0.226) GC TO 25 00003930

____GRCCSE=-_C017+NzC-_-6734+NzC-0987+NzC70-5419+NzC-179-0345}}______10003940 1) 00003950 GC TO 27 00003960 25.....IF(W.GT.0.55) GO.TO.26 00003970

GRCCSF=0.+V*(-12.8306+W*(213.4645+W*(-1172.8346+W*(1816.7802 00003980 1+b*(4769.9642+W*(-20782.9608+W*(26637.2442+W*(-11791.4688 00003990 --- --111111111 __ 30004060 GO TO 27 GRDCSF=.211956-1.35*(W-.55) 26

...IE(L.GILO.707A.GROCSEZO...... -- ---- - 00004030 CEPCPM=-2.3861+W*(34.2316+W*(-266.8938+W*(250.2859+W*(3745. 27 00004640 17636+b+(-12450.4146+W+(11267.6934))))) 00004050

	CETCPY=CEFCFM/1000.	00004070
	GRTGFT=-0.0001+6+(1.4988+W*(-57.9098+.*(779.1001+W*(-4204.	00004080
	11758+**(10512-7643+**(-12167-2788+**(3919-3533)))))	00004050
	IF(2.GT.0.315) GROCPM=0.	20064100
	IF (> GT . C . 35) GO TO 2P	00004110
	GRUCY 4== 0069+4x (1-3799+4+(-13-6714+4+(-1-2748+4+41274-55 -	00004120
	193+1 * (-13035.8662+W* (59190.0797+W* (-127927.2065+W* (106845.	
	17562))))))	00004140
	50 TO 29	00004150
28	GFFCYM=16.9481+W+(-131.5322+W+(388.4930+W+(+554.3724+W+	00004160
	1(365-7019+#+(-105-2687)))))	
29	CEPCYM=1.162+W*(14.8842+W*(-169.1+34+H*(822.1258+W*(-3	
• .	1053.1573+4*(7474.2581+%*(-10069.5247+%*(6758.6616+%*	20004190
	- 1(-1774-5125)-))-)	
	CEPCYM=CEPCYM/1000.	20004210
	CTEASE=GRADCT+(COLL-CEPTCT)	00004223
	CFRASE=GRAGCP+CTEASE+CERTGP	
	CAFHAS=GROCNF+CTBASE+CEPCNF	00004240
	CSFEAS=GRUCSF+CTEASE+CEPCSF	00004250
	CFMRAS=GECCFM+CISASE+CEPCPM	00004260
	CYYFAS#GROCYM*CTBASE+CEPCYM	30304270
	CT=CTHASE+DELCT	00004260
	CP=CPRASE +CELCP	00004290
	CSF=CSF8 AS+BELCSF	00540000
	CNF=CNFFAS+CELCNF	00004310
	CFM=CPMRAS+GELGRM	00004320
	CYM=CYMP AS+DELCYM	00004330
	RETURN	00004340
	ENC	
	FUNCTION GK(G.DUM.I.J)	00004360
	CIMENSION G(8.5.8)	00004370
	CK=3(I+J+1)+DUM+(G(I+J+2)+BUM+(G(I+J+3)+BUM+(G(I+J+4)+BUM+	00064380
	1(G(I.J.5)+DUM*(G(I.J.6)+DUM*(C(I.J.7)+DUM*(C(I.J.8))))))	000043-0
	RETURM	00004400
	END.	00004410